Double Gamow-Teller transitions and its relation to neutrinoless $\beta\beta$ decays

Javier Menéndez

Center for Nuclear Study, The University of Tokyo

with N. Shimizu (CNS) and K. Yako (CNS)

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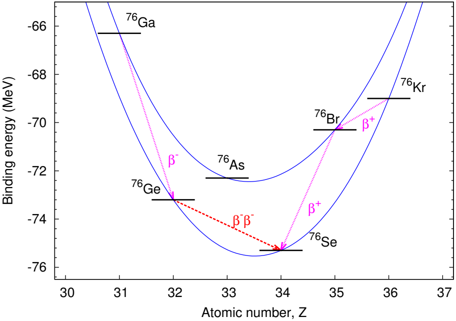
CNS Graduate School of Science University of Tokyo
Center for Nuclear Study (CNS)

東京大学 THE UNIVERSITY OF TOKYO

Nuclear $\beta\beta$ decay

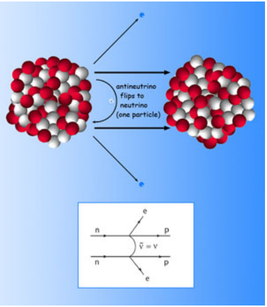
$\beta\beta$ decay second order process observable if β-decay is energetically forbidden or hindered by large ΔJ

Neutrinoless double-beta decay ($0\nu\beta\beta$):
Lepton-number violation, Majorana nature of neutrinos



$Q_{\beta\beta} > 2$MeV

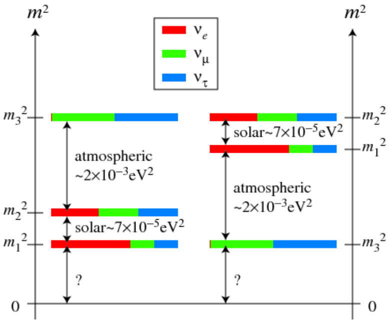
^{48}Ca $\to$ ^{48}Ti
^{76}Ge $\to$ ^{76}Se
^{82}Se $\to$ ^{82}Kr
^{96}Zr $\to$ ^{96}Mo
^{100}Mo $\to$ ^{100}Ru
^{110}Pd $\to$ ^{110}Cd
^{116}Cd $\to$ ^{116}Sn
^{124}Sn $\to$ ^{124}Te
^{130}Te $\to$ ^{130}Xe
^{136}Xe $\to$ ^{136}Ba
^{150}Nd $\to$ ^{150}Sm

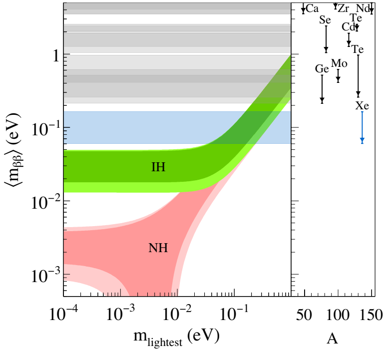


$0\nu\beta\beta$ decay matrix elements and experiment

The decay lifetime is $$T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

sensitive to absolute neutrino masses, $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$, and hierarchy





KamLAND-Zen, PRL117 082503(2016)

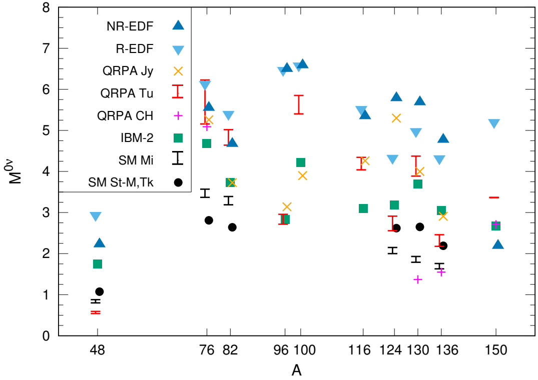
Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

$$\langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\,\Omega^X\, |0_i^+\rangle$$

Ω^X = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$),Tensor
$H(r)$ = neutrino potential



Engel, JM, Rep. Prog. Phys. 80 046301 (2017)

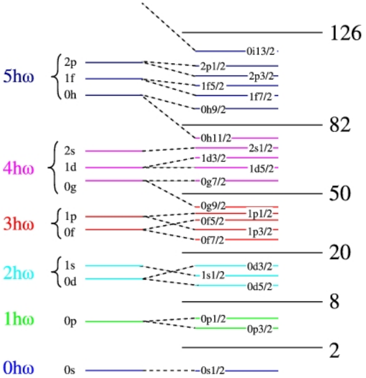
How can nuclear matrix elements calculations improve?

Talks by Simkovic, Coraggio (Mon), Suhonen, Barea (Tue)

Can nuclear structure experiments guide $0\nu\beta\beta$ decay?

Talks by Ejiri (Mon), Freckers (Sat)

Configuration space



Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbits: always empty
- Configuration space: where many-body problem is solved
- Inert core: always filled

$$H\,|\Psi\rangle = E\,|\Psi\rangle \;\rightarrow H_{eff}\,|\Psi\rangle_{eff} = E\,|\Psi\rangle_{eff}$$

$$|\Psi\rangle_{eff} = \sum_\alpha c_\alpha\,|\phi_\alpha\rangle\,, \quad |\phi_\alpha\rangle = a^+_{i1}a^+_{i2}...a^+_{iA}\,|0\rangle$$

Shell model codes (1 major oscillator shell) $\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

QRPA calculations suggest larger spaces ($\gtrsim$ 2 major shells) needed

Dimension $\sim$

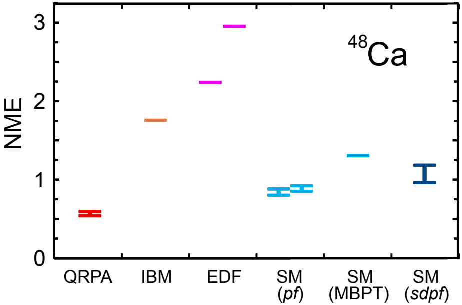
$$\binom{(p+1)(p+2)_\nu}{N}\binom{(p+1)(p+2)_\pi}{Z}$$

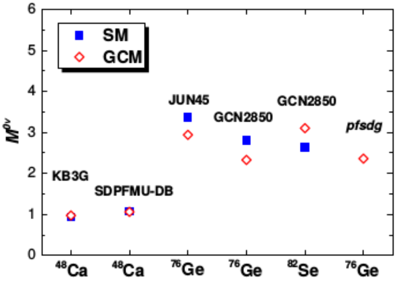
Shell model matrix elements in two shells

^{48}Ca$\rightarrow$^{48}Ti $0\nu\beta\beta$ decay

Enlarge configuration space from *pf* to *sdpf*, 4 to 7 orbitals

Test excitation energy of 0_2^+ in ^{48}Ca off by 1.3MeV in *pf* shell





Nuclear matrix element increases moderately 30%

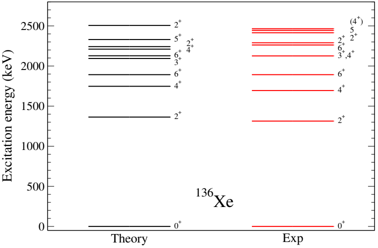
Iwata et al. PRL116 112502 (2016)

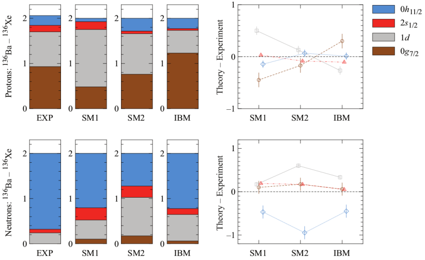
Likewise, very mild effect found in GCM calculations of ^{76}Ge

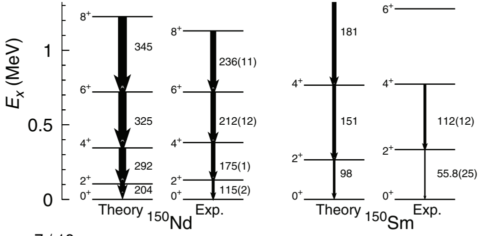
Jiao et al. arXiv:1707.03940

Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)

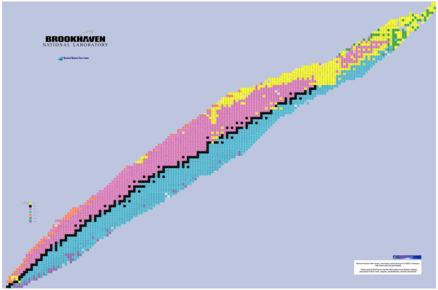
Rodríguez et al. PRL105 252503 (2010)

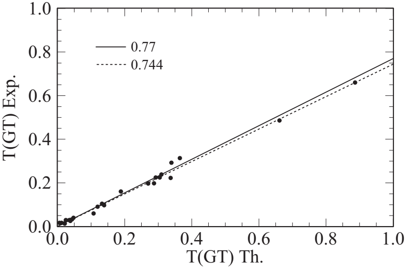
...

Vietze et al. PRD91 043520 (2015)

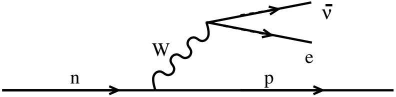
Nuclear β decays

β decays (e^- capture) main decay model along nuclear chart
In general well described by nuclear structure theory: shell model...





Martinez-Pinedo et al. PRC53 2602(1996)

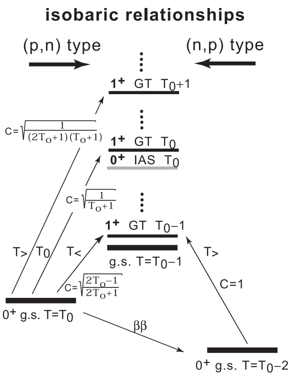


$$\langle F| \sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\rm eff} |I\rangle\,, \quad [\boldsymbol{\sigma}_i \tau]^{\rm eff} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

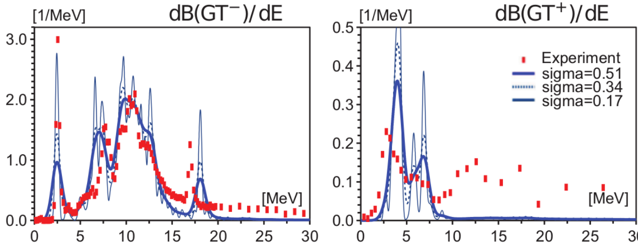
Gamow-Teller transitions:
theory needs $\boldsymbol{\sigma}_i \tau$ "quenching"

Gamow-Teller strength distributions

Gamow-Teller (GT) distributions well described by theory (quenched)



Freckers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)

$$\langle 1_f^+ | \sum_i [\boldsymbol{\sigma}_i \tau_i^\pm]^{\text{eff}} | 0_{\text{gs}}^+ \rangle\,, \quad [\boldsymbol{\sigma}_i \tau^\pm]^{\text{eff}} \approx 0.7 \boldsymbol{\sigma}_i \tau^\pm$$

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \boldsymbol{\sigma}_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \boldsymbol{\sigma}_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

Recent experimental plans in RCNP, RIKEN (^{48}Ca), INFN Catania

Takaki et al. JPS Conf. Proc. 6 020038 (2015)

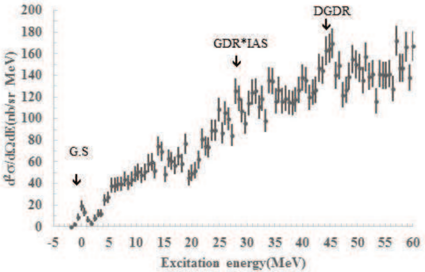
Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Talks by Ejiri, Lenske (Mon), Yako, Lay (Tue), Carbone (Thu)

Promising connection to $\beta\beta$ decay,
two-particle-exchange process,
especially the (tiny) transition
to ground state of final state

Two-nucleon transfers related to
$0\nu\beta\beta$ decay matrix elements

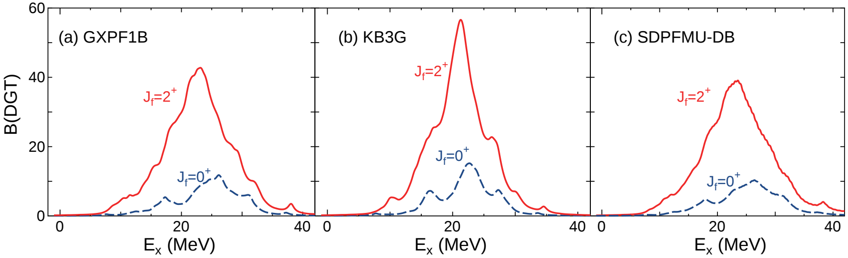
Brown et al. PRL113 262501 (2014)



^{48}Ca Double Gamow-Teller distribution

Calculate with shell model ^{48}Ca 0^+_{gs} Double Gamow-Teller distribution

$$B(DGT^-;\lambda;i\to f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\left\|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^- \times \sum_j \boldsymbol{\sigma}_j\tau_j^-\right]^{(\lambda)}\right\|{}^{48}\mathrm{Ca}_{gs}\right\rangle\right|^2$$



Shell model calculation with Lanczos strength function method

Double GT resonances in one and two shells rather similar result

Shimizu, JM, Yako, arXiv:1709.01088

Double Gamow-Teller distribution and pairing

Study the sensitivity of Double GT distribution to pairing correlations

Add/remove pairing

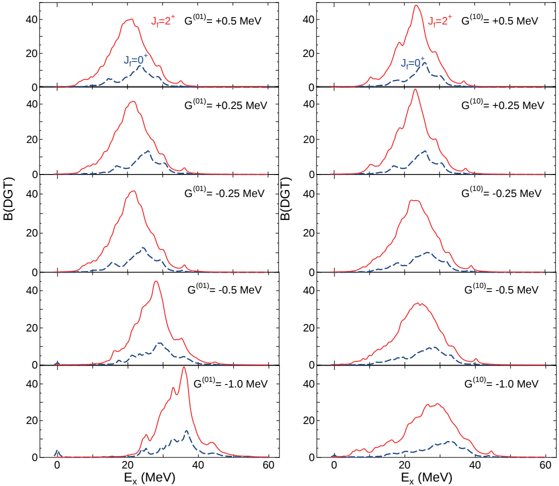
$$H' = H + G^{JT} P^{JT}$$

like-particle (T=1) or proton-neutron (T=0)

Position of the DGT giant resonance very sensitive to like-particle pairing

DGT resonance width probes isoscalar pairing

Shimizu, JM, Yako, arXiv:1709.01088

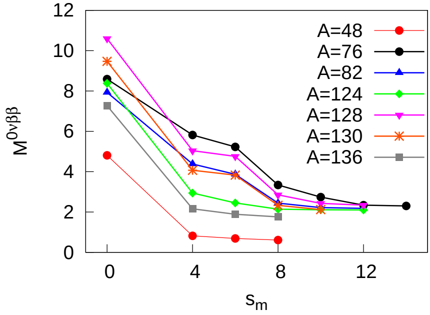


Pairing correlations and $\beta\beta$ decays

$0\nu\beta\beta$ decay favoured by (isovector) pairing, disfavored isoscalar pairing

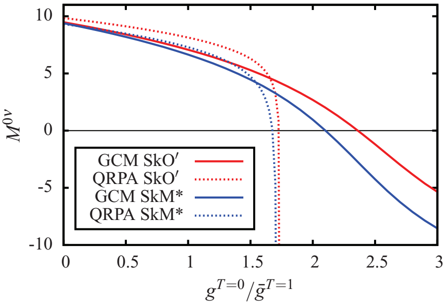
Talk by Hinohara (Fri)

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value

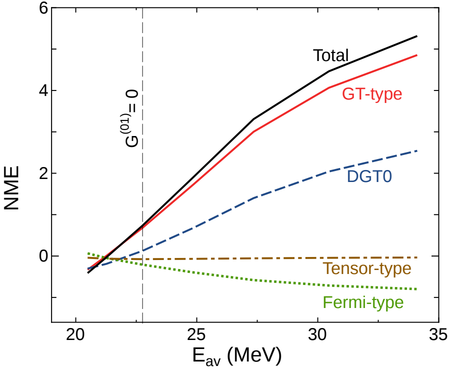


Hinohara, Engel PRC90 031301 (2014)

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

^{48}Ca DGT resonance and $0\nu\beta\beta$ decay

Correlation between Double Gamow-Teller resonance in ^{48}Ca and $0\nu\beta\beta$ decay nuclear matrix element



Energy of DGT resonance with accuracy to ∼1MeV, can give insight on the value of $0\nu\beta\beta$ decay nuclear matrix element

$$E_{\rm av} = \frac{\sum_f E_f B(DGT^-, i \to f)}{\sum_f B(DGT^-, i \to f)}$$

Might be feasible in near future

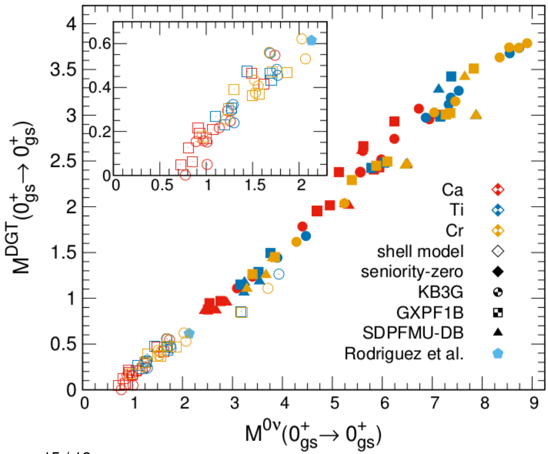
Shimizu, JM, Yako, arXiv:1709.01088

In progress: sensitivity to other nuclear structure correlations

DGT to ground state and $0\nu\beta\beta$ decay

DGT transition to ground state of final nucleus:
Ca, Ti, Cr isotopic chains

$$M^{\rm DGT} = \langle {\rm Final_{gs}} || \left[\sum_i \boldsymbol{\sigma}_i \tau_i^- \times \sum_j \boldsymbol{\sigma}_j \tau_j^- \right]^0 || {\rm Initial_{gs}} \rangle |^2$$

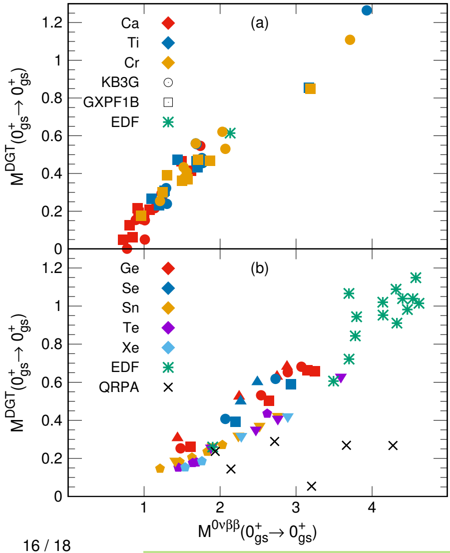


Very good linear correlation between DGT and $0\nu\beta\beta$ decay nuclear matrix elements

Linerar correlation holds for $\sim$ 25 transitions studied for simplified wf's (seniority-zero), for different interactions

Shimizu, JM, Yako, arXiv:1709.01088

DGT and $0\nu\beta\beta$ decay: heavy nuclei



DGT transition to ground state

$$M^{\rm DGT} = \sqrt{B(DGT_-; 0; 0^+_{\rm gs} \to 0^+_{\rm gs})}$$

very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements

Correlation holds across wide range of nuclei, from Ca to Ge and Xe

Common to shell model and energy-density functional theory
$0 \lesssim M^{0\nu\beta\beta} \lesssim 5$
disagreement to QRPA

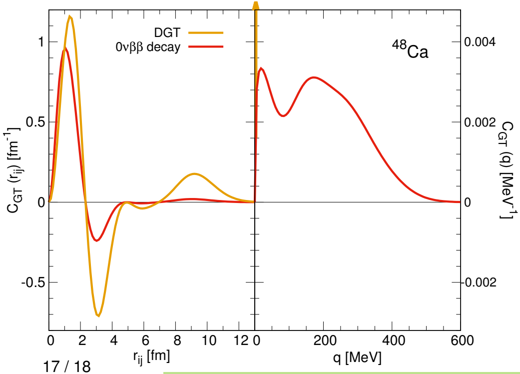
Shimizu, JM, Yako, arXiv:1709.01088

Short-range character of DGT, $0\nu\beta\beta$ decay

DGT transition to ground state same initial, final states with $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)



$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

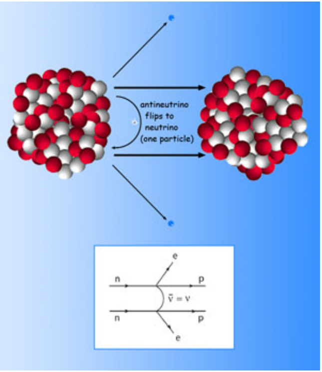
Long-range part dominant in QRPA DGT matrix elements!

Shimizu, JM, Yako, arXiv:1709.01088

Summary

Nuclear matrix elements are key
for the design of next-generation tonne-scale $0\nu\beta\beta$ decay experiments
and for fully exploiting the experimental results

- Present matrix element calculations disagree
  Need improved calculations,
  guidance from other nuclear experiments
- Shell model nuclear matrix elements
  in two shells for ^{48}Ca, ^{76}Ge,
  suggest moderate enhancement ($\lesssim 30\%$)
- Double Gamow-Teller transitions
  pursued in RIKEN, INFN LNS, RCNP Osaka
  can provide very useful insight on
  value of $0\nu\beta\beta$ decay matrix elements



Collaborators

東京大学 THE UNIVERSITY OF TOKYO	**T. Otsuka** **T. Abe**	Graduate School of Science, University of Tokyo — Center for Nuclear Study (CNS)	**N. Shimizu** **Y. Tsunoda** **K. Yako**
JAEA	**Y. Utsuno**	THE UNIVERSITY OF AIZU 会津大学	**M. Honma**
TECHNISCHE UNIVERSITÄT DARMSTADT	E. A. Coello Pérez G. Martínez-Pinedo A. Schwenk	האוניברסיטה העברית בירושלים The Hebrew University of Jerusalem	D. Gazit
UAM UNIVERSIDAD AUTONOMA DE MADRID	A. Poves T. R. Rodríguez	THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL	J. Engel
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG	E.Caurier F. Nowacki		N. Hinohara
			Y. Iwata