Shell Model Calculations of the Nuclear Matrix Elements for the Neutrinoless Double Beta Decay

A. Neacsu[1,2]

[1] IFIN-HH, Magurele Bucharest
[2] "Horia Hulubei" Foundation, Magurele Bucharest

Seminar DFT 2012

Summary

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1. Brief history of $\beta\beta$ decay and ν physics

2. $0\nu\beta\beta$ decay
   - Present experimental status, limits and difficulties
   - Motivation
   - Details of the calculation

3. Numerical results and conclusions

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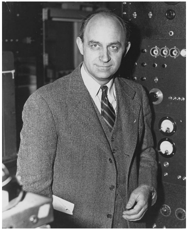

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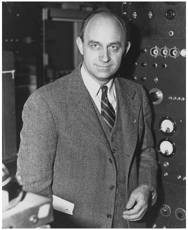

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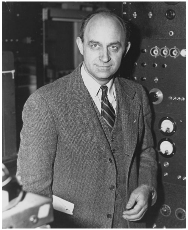

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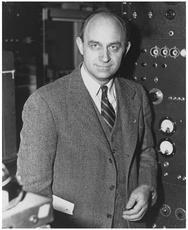

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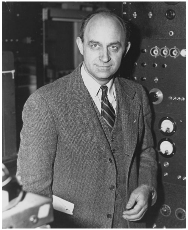

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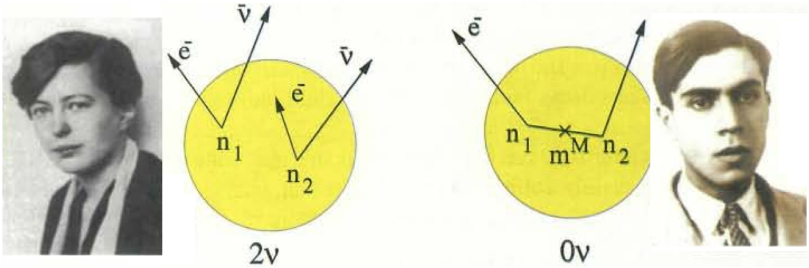

Figure: Maria Goeppert-Mayer and Ettore Majorana

Althow the phenomenon of nuclear $\beta\beta$ decay was closely connected to the the question of lepton number conservation and the nature and mass of the ν, M. Goeppert-Mayer performed the first $\beta\beta$ calculations to study the stability of even-even nuclei over geological time.

The first $\beta\beta$ calculations

- 1935 - First calculation of $2\nu\beta\beta$ decay - M. Goeppert-Mayer (1935)
- 1939 - First calculation of $0\nu\beta\beta$ decay - W.H. Furry (1939), on the basis of E. Majorana (1937) and C Racah (1937)

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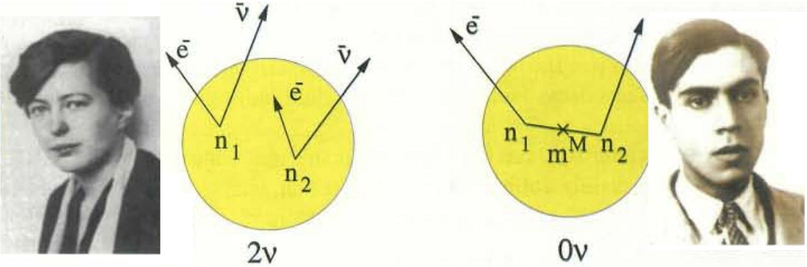

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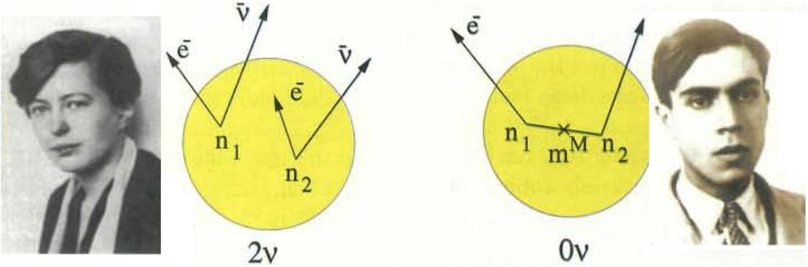

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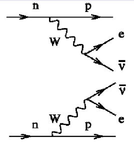
The "traditional" $\beta\beta$ decay modes

$2\nu\beta\beta$

- $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$,
- $\Delta L = 0$
- $\mid T^{2\nu}_{1/2} \mid^{-1} = G^{2\nu}\left(Q_{\beta\beta}, Z\right) \mid M_{2\nu} \mid^2 \sim \mid 10^{20} y \mid^{-1}$,



$0\nu\beta\beta$

- $(Z, A) \rightarrow (Z+2, A) + 2e^-$,
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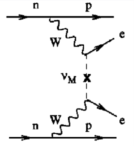
- $\mid T^{0\nu}_{1/2} \mid^{-1} = G^{0\nu}\left(Q_{\beta\beta}, Z\right) \mid M^{0\nu} \mid^2 < m^2_{\beta\beta} > \sim \mid 10^{25} y \mid^{-1}$,
- $< m_{\beta\beta} > = \mid \sum_i U^2_{ei} m_i \mid$



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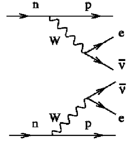

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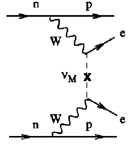

First observations of $\beta\beta$ decay

Correct observations

- 1949 - First experimental limit with Geiger counter measuring 25g ^{124}Sn by E.L. Fireman.
- 1950 - First geochemical observation of $\beta\beta$ decay of ^{130}Te by M.G. Inghram & J.H. Reynolds
- 1967 - First direct experiment with Ge by E. Fiorini et al
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- 1949 - First experimental limit with Geiger counter measuring 25g ^{124}Sn by E.L. Fireman.
- 1950 - First geochemical observation of $\beta\beta$ decay of ^{130}Te by M.G. Inghram & J.H. Reynolds
- 1967 - First direct experiment with Ge by E. Fiorini et al
- 1968 - First geochemical observation of ^{82}Se by T. Kirsten

False observations

- 1949 - $0\nu\beta\beta$ decay - at 2.6σ in ^{124}Sn by E.L. Fireman - most likely, measured a radioactive contamination
- 1953 - indication of $\beta\beta$ decay of ^{96}Zr by John A. McCarthy
- 1955 - strong evidence of $0\nu\beta\beta$ decay of ^{48}Ca by John A. McCarthy

The early stage for theories of $\beta\beta$ decay

When E. Fermi and Mayer wrote their papers, little distinction was made between ν and $\bar{\nu}$.

While β^- emitters were known to occur naturally, β^+ emitters had only just been observed by F. Joliot and I. Joliot-Curie.

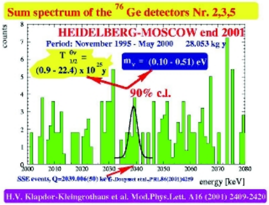
De Broglie and C.C. Wick recognized in 1934 that the neutral particles associated with the two processes could be different, and de Broglie introduced the term antineutrino, but it was not until the work of E. Majorana, and its elaboration by G. Racah, that the possibility of a clear physical distinction, or alternatively, of a complete identity, between neutrinos and antineutrinos was better understood.

Racah observed that if the ν is a Majorana particle, it must have no magnetic moment and the same neutral particle is emitted in both β^- and β^+ decay. To test the latter property he proposed to take the neutral particle from one β^- decay and to see whether it could induce another β^- decay.

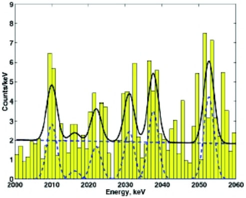
In 1955 R. Davis carried out this test using a reactor ν source producing mainly $\bar{\nu}$ and the reaction: $\nu +^{37} Cl \rightarrow e^- +^{37} Ar$ as the stimulated emission,

Furry realized that the ν in the two-stage process did not necessarily have to be real as in the reactor experiment, but could be virtual - in $0\nu\beta\beta$ decay. The virtual exchange in $0\nu\beta\beta$ decay has finally proved to be the most sensitive test for Majorana ν, mainly because the phase space of the virtual ν is much larger than for the real ν in the Davis experiment.

2001

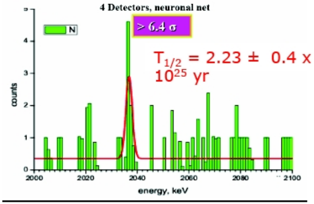


2004

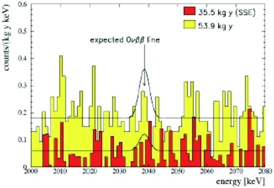


H.V. Klapdor-Kleingrothaus et al.,
Phys. Lett. B 586, 198 (2004)

2006

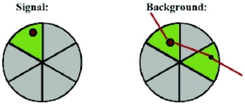


Mod.Phys.Lett.A21:1547-1566 (2006)



H.V. Klapdor-Kleingrothaus et al.,
Eur.Phys.J. A12 (2001) 147-154

Background reduction by pulse shape analysis



Very controversial discussion in the community

If right, neutrino mass is around 0.3 eV
and masses are almost degenerate

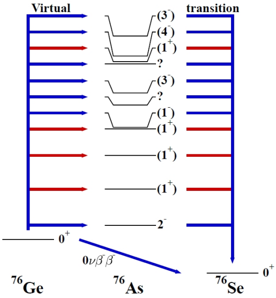
Figure: The H.V. Klapdor-Kleingrothaus experimental $0\nu\beta\beta$ decay claim with ^{76}Ge source=detectors as result of the Heidelberg-Moscow collaboration

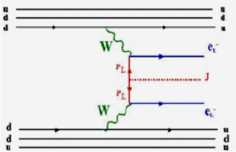
The recent years - other running and future experiments

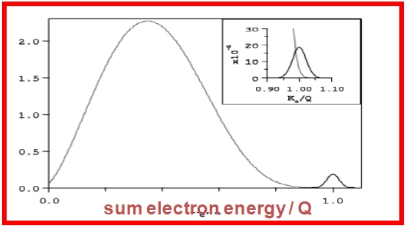
Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011	0.17-0.42
		40	2×10^{26}	in progress	$\sim$ 2012	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26}*$	in progress	$\sim$ 2013	0.018-0.037
			$2.1 \times 10^{26}**$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	$\sim$ 2011	0.073-0.18
		1000	8×10^{26}	R&D	$\sim$ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	$\sim$ 2011	0.03-0.07
		1000	10^{27}	R&D	$\sim$ 2013-15	0.02-0.046
SNO+	^{150}Nd	132	1.8×10^{25}	in progress	$\sim$ 2014	0.09-0.18

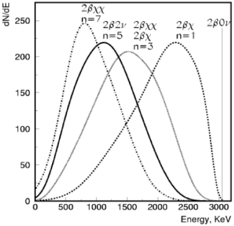
Figure: The present experiments, their status and sensitivity

The recent years - what do these experiments search for?

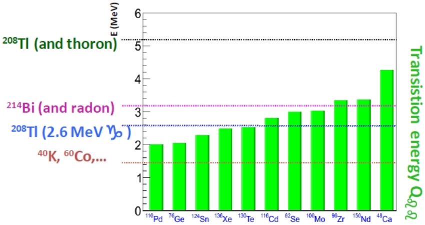






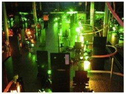


The recent years - background problem and choise of isotopes



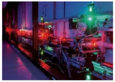
Nucleus	Existing method	R&D
^{48}Ca		Laser separation, gazeous diffusion
^{76}Ge	Centrifugation	
^{82}Se	Centrifugation	
^{96}Zr		Laser separation
^{100}Mo	Centrifugation	
^{116}Cd	Centrifugation	
^{130}Te	Centrifugation	
^{136}Xe	Centrifugation	
^{150}Nd		Centrifugation, Laser

R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



R&D in Russia for ^{150}Nd enrichment by centrifugation

R&D in France for ^{150}Nd enrichment by laser



SPLG 2012
12th Workshop on Separation Phenomena in Liquids and Gases
Paris June 3-8 2012
Dedicated session for Double beta

If $0\nu\beta\beta$ is so difficult, why bother? - Motivation

The $0\nu\beta\beta$ decay is more than just a search for the ν mass. Lepton number violation is just as important as Barion number violation.

- $\mathcal{L}$ and $\mathcal{B}$ are only ACCIDENTALY conserved in the SM.
- The need for an effective theory: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_{LNV} + \frac{1}{\Lambda^2}\mathcal{L}_{LFV,BNV,LNV} + \dots$
- In baryogenesis $\mathcal{B}$ is violated
- $\mathcal{L}$ and $\mathcal{B}$ are often connected in GUTs
- GUTs have seesaw and Majorana ν

In order to perform correct $0\nu\beta\beta$ predictions, we need accurate calculations of the NMEs involved in the half life expression.

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In order to perform correct $0\nu\beta\beta$ predictions, we need accurate calculations of the NMEs involved in the half life expression.

Details of the calculation

The $0\nu\beta\beta$ decay $(Z, A) \rightarrow (Z+2, A) + 2e^-$ requires the neutrino and the antineutrino to be identical, massive particles. Taking into account light neutrinos in the presence of left-handed weak interactions, we express the lifetime:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(E_0, Z) \mid M^{0\nu} \mid^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2 , \quad (1)$$

$G^{0\nu}$ is the leptonic phase space factor depending on the energy decay E_0 and nuclear charge Z, and $\langle m_\nu \rangle$ is the effective neutrino mass parameter depending on the first row elements of the neutrino mixing matrix U_{ei}, Majorana phases $e^{i\alpha_i}$ and the absolute neutrino mass eigenstates m_i. The NMEs are:

$$M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 \cdot M_F^{0\nu} , \quad (2)$$

where $M_{GT}^{0\nu}$ and $M_F^{0\nu}$ are the Gamow-Teller (GT) and the Fermi(F) parts, respectively.

$$M_\alpha^{0\nu} = \sum_{m,n} \langle 0_f^+ \| \tau_{-m} \tau_{-n} O_{mn}^\alpha \| 0_i^+ \rangle , \quad (3)$$

where O_{mn}^α are transition operators ($\alpha = GT, F$) and the summation is over all the nucleon states.

Details of the calculation

Due to the two-body nature of the transition operator, the matrix elements are reduced to sum of products of two-body transition densities (TBTD) and matrix elements for two-particle states (TBME),

$$M_\alpha^{0\nu} = \sum_{j_p j_{p'} j_n j_{n'} J_\pi} TBTD\left(j_p j_{p'}, j_n j_{n'}; J_\pi\right) \left\langle j_p j_{p'}; J_\pi \| \tau_{-1}\tau_{-2} O_{12}^\alpha \| j_n j_{n'}; J_\pi \right\rangle ,$$

The two-body transition operators O_{12}^α can be expressed in a factorized form as:

$$O_{12}^\alpha = N_\alpha S_\alpha^{(k)} \cdot R_\alpha^{(k)}$$

where N_α is a numerical factor including the coupling constants, and $S_\alpha^{(k)}$ and $R_\alpha^{(k)}$ are operators acting on the spin and relative wave functions of two-particle states. Thus, the calculation of the matrix elements of these operators can be decomposed into products of reduced matrix elements within the two subspaces. The expressions of the two-body transition operators are:

$$O_{12}^{GT} = \sigma_1 \cdot \sigma_2 H(r) , \quad O_{12}^F = H(r) .$$

The neutrino potential and finite nucleon size effects (FNS)

The neutrino potential is of Coulomb type, depending weakly on the intermediate states, and is defined by integrals of momentum carried by the virtual neutrino exchanged between the two nucleons [**?**]

$$H_\alpha(r) = \frac{2R}{\pi}\int_0^\infty j_0(qr)\frac{h_\alpha(q)}{\omega}\frac{1}{\omega+\langle E\rangle}q^2dq \equiv \int_0^\infty j_0(qr)V_\alpha(q)q^2dq\ , \quad (4)$$

where $R = 1.2A^{1/3}$ fm, $\omega = \sqrt{q^2+m_\nu^2}$ is the neutrino energy and $j_0(qr)$ is the spherical Bessel function. We use the closure approximation in our calculations, and $\langle E\rangle$ represents the average excitation energy of the states in the intermediate odd-odd nucleus, that contribute to the decay. The expressions of $h_\alpha(\alpha = F, GT)$ are

$$h_F = G_V^2(q^2) \quad (5)$$

and

$$h_{GT}(q^2) = \frac{G_A^2(q^2)}{g_A^2}\left[1-\frac{2}{3}\frac{q^2}{q^2+m_\pi^2}+\frac{1}{3}\left(\frac{q^2}{q^2+m_\pi^2}\right)^2\right]+\frac{2}{3}\frac{G_M^2(q^2)}{g_A^2}\frac{q^2}{4m_p^2}\ , \quad (6)$$

where m_π is the pion mass, m_p is the proton mass and

$$G_M(q^2) = (\mu_p-\mu_n)G_V(q^2), \quad (7)$$

with $(\mu_p-\mu_n) = 4.71$.

$$G_A\left(q^2\right) = g_A\left(\frac{\Lambda_A^2}{\Lambda_A^2+q^2}\right)^2,\ G_V\left(q^2\right) = g_V\left(\frac{\Lambda_V^2}{\Lambda_V^2+q^2}\right)^2 \quad (8)$$

$g_V = 1$, $g_A = 1.25$, and we used $\Lambda_V = 850 MeV$, $\Lambda_A = 1086 MeV$.

Short range corellations (SRC)

When computing the radial matrix elements
$\langle nl|H_\alpha|n'l'\rangle$ we use the harmonic oscillator wave functions $\psi_{nl}(r)$ and $\psi_{n'l'}(r)$ corrected by a factor $[1 + f(r)]$, which takes into account the nuclear interaction short range correlations:

$$\psi_{nl}(r) \rightarrow [1 + f(r)]\,\psi_{nl}(r)\ .$$

For the correlation function we take the functional form

$$f(r) = -c \cdot e^{-ar^2}\left(1 - br^2\right)\ ,$$

where a, b and c are constants which have particular values for in different parameterizations.
Including HOC and FNS effects the radial matrix elements of the neutrino potentials becomes:

$$\langle nl \mid H_\alpha(r) \mid n'l'\rangle = \int_0^\infty r^2 dr \psi_{nl}(r)\psi_{n'l'}(r)\,[1 + f(r)]^2 \times \int_0^\infty q^2 dq V_\alpha(q) j_0(qr)\ ,$$

where ν is the oscillator constant.
The *HO* radial wave functions are given by:

$$\psi_{nl}(r) = N_{nl}\ exp\left(-\frac{\nu r^2}{2}\right) r^l\ L_n^{(l+\frac{1}{2})}\nu r^2\ , \qquad (9)$$

where N_{nl} is the normalization constant and $L_n^{(l+\frac{1}{2})}(\nu r^2)$ are the Laguerre associated polynomials

SRC+FNS

$$N_{nl} = \left[\frac{2^n n!}{(2l+2n+1)!!}\right]^{\frac{1}{2}} (2\nu)^{\frac{2l+3}{4}} \left(\frac{2}{\pi}\right)^{\frac{1}{4}} \tag{10}$$

$$\begin{aligned} L_n^{(l+\frac{1}{2})}(\nu r^2) &= \frac{(2l+2n+1)!!}{2^n n!} \\ &\times \sum_{k=0}^{n} \binom{n}{k} \frac{1}{(2l+2k+1)!!} \left(-2\nu r^2\right)^k . \end{aligned} \tag{11}$$

$$\psi_{nl}(r)\psi_{n'l'}(r) = \sum_{s=0}^{n+n'} A_{l+l'+2s}(nl, n'l') \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \times (2\nu)^{\frac{l+l'+2s+3}{2}} e^{-\nu r^2} r^{l+l'+2s},$$

This leads us to perform integrals of the form:

$$\mathcal{I}_\alpha(\mu; m) = \int_0^\infty q^2 dq\, V_\alpha(q) \times \left(\frac{2}{\pi}\right)^{\frac{1}{2}} (2\nu)^{\frac{m+1}{2}} \int_0^\infty dr\, e^{-\mu r^2} r^m j_0(qr)$$

where $\mu = \nu$, $\nu + a$, $\nu + 2a$ and m is integer.

In the table below our results are presented, which are in good agreement with previous ones, provided that the same nuclear nuclear effects are included in the calculations. For ^{48}Ca we used GXPF1A effective interaction in the full *pf* model space, and for ^{82}Se we used JUN-45 effective interactions in the *jj*44 model space. The TBTD were computed using ANTOINE ShM Code.

$M^{0\nu}$	^{48}Ca	^{82}Se
$^{(*)}$ present work	0.573	2.47
[1] (2010 ShM)	0.57	
[2] (2008 ISM)	0.59	2.11
[3] (2009 ISM)	0.61	2.18
[4] (2007 QRPA)		2.77

Table: Comparison between the results of the present work $^{(*)}$ and other similar results from the references indicated. In the calculation we used SRC of Jastrow type, FNS and HOC.

[1] M. Horoi and S. Stoica, Phys. Rev. **81**, 024321 (2010)

[2] E. Caurier, J. Menendez, F. Nowacki, and A. Poves, Phys. Rev. Lett. **100**, 052503 (2008)

[3] J. Menendez, A. Poves, E. Caurier, F. Nowacki, and A. Poves, Nuclear Physics **A 818** 139-151 (2009)

[4] Markus Kortelainen and Jouni Suhonen, Phys. Rev. C **75** 051303(R) (2007)

The influence of several effects on the NMEs

In the next we observe the influence of the effective interaction, the FNS, HOC and SRC effects on the NMEs in the case of ^{48}Ca. We have compared the GXPF1A and KB3G interactions and found very little influence due to the chosen effective interaction. This is in agreement with other published ShM calculations. Next, we analyse the importance of the FNS and HOC, which decrease the NME by about 30%. A further decrease is also obtained by using the SRC and the magnitude of this varies with the parametrisation selected. The Miller-Spencer SRC has an important influence on the results, while Argonne-V18 and CD-Bonn parameterizations present a softer reduction of the NMEs.

^{48}Ca		GXPF1A			KB3G	
	$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}$	$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}$
BARE	-0.980	0.220	-1.122	1.148	-0.244	1.303
FNS	-0.823	0.161	-0.926	0.969	-0.176	1.050
FNS+HOC	-0.754	0.138	-0.842	0.887	-0.151	0.984
SRC(MS)	0.623	-0.128	0.705	0.740	-0.138	0.829
SRC(MS)+FNS	0.588	-0.109	0.658	-0.701	0.117	-0.776
SRC(MS)+FNS+HOC	0.5168	-0.088	0.573	-0.618	0.094	-0.679
SRC(AV18)	0.862	-0.190	0.984	1.014	-0.208	1.147
SRC(AV18)+FNS	0.797	-0.158	0.898	-0.940	0.172	-1.050
SRC(AV18)+FNS+HOC	0.708	-0.131	0.796	-0.834	0.143	-0.925
SRC(CD-BONN)	0.969	-0.218	1.109	1.136	-0.240	1.290
SRC(CD-BONN)+FNS	-0.863	0.172	-0.973	1.014	-0.189	1.135
SRC(CD-BONN)+FNS+HOC	0.775	-0.145	0.868	0.912	-0.159	1.013

Conclusions

First conclusion

One main conclusion is that the interplay between the effects and correlations is important and should not be negleted in the calculations of $0\nu\beta\beta$ decay as they can reduce the value of the NME by a significant amount. This variation of the NME manifests itself at the power of two and thus can influence the expected halflives, as well as the effective neutrino mass parameter.

Second conclusion

Another conclusion is that the choice of the effective interaction is not a major concern, as one can see that any interaction which describes well the region of interest will provide similar results.

Most important conclusion

The code that we have developed provides results in good ageement with other similar computations and thus, provides an usefull tool in the studies of $0\nu\beta\beta$ decay.

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Thank you!