ELECTRON ANGULAR CORRELATION IN NEUTRINOLESS DOUBLE BETA DECAY AND NEW PHYSICS

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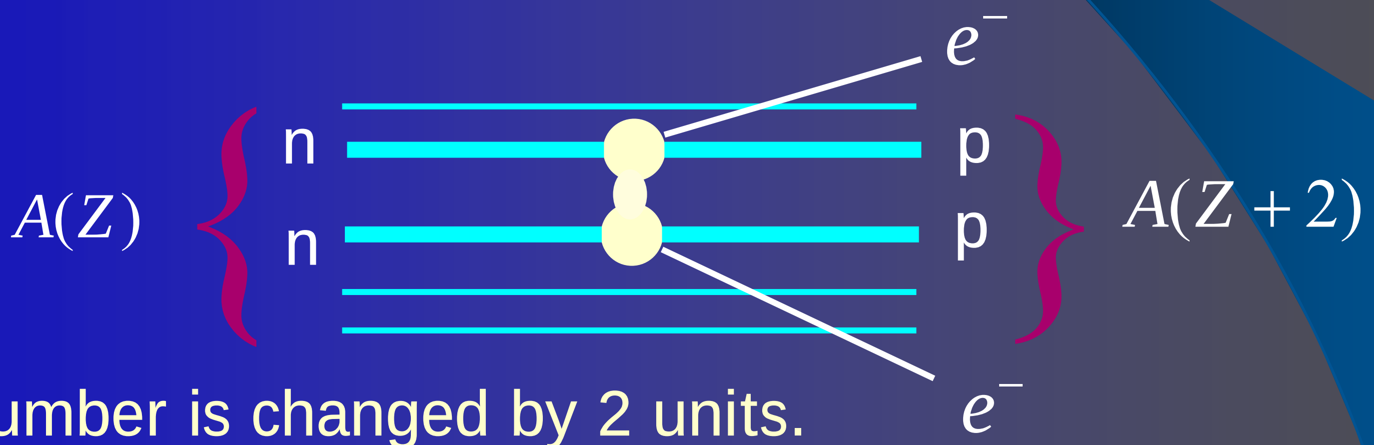
Introduction

Neutrinos have non-zero masses and they mix with each other.
It is largely anticipated that the neutrinos are Majorana particles.

- $0\nu 2\beta - \text{decay}$ $\quad A(Z) \rightarrow A(Z+2) + 2e^{-}$



Lepton number is changed by 2 units.
$0\nu 2\beta$ decay is forbidden in the SM.

Extended version of the SM could contain tiny nonrenormalizable terms that violate LN and allow $0\nu 2\beta$ decay.

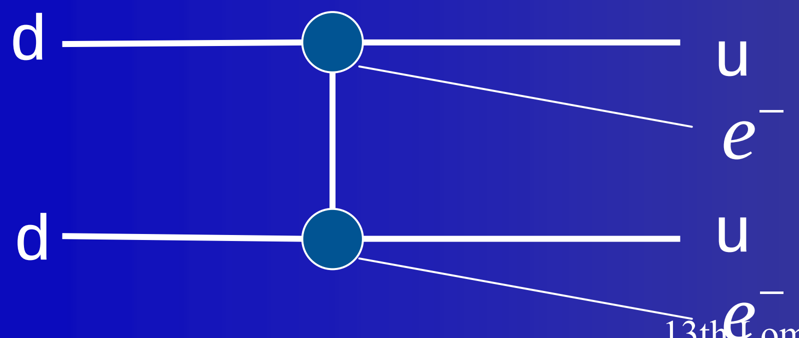
Probable mechanisms of LN violation may include exchanges by:

- Majorana neutrinos
- Scalar bilinears, e.g. doubly charged dileptons
- SUSY Majorana particles
- Leptoquarks
- Right-handed W_R bosons etc.

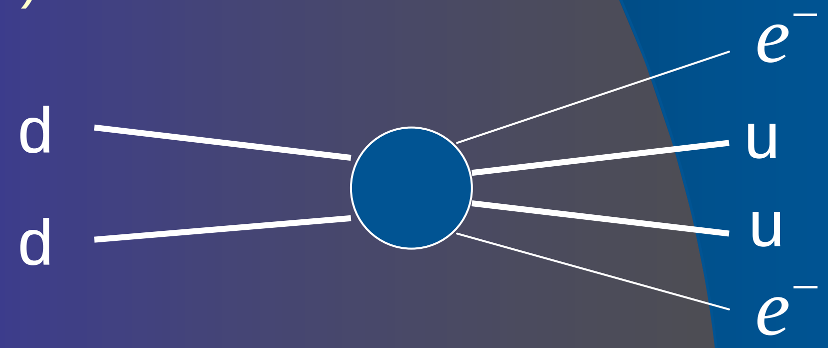
Two possible classes of mechanisms for the $0\nu 2\beta$ decay:

Long range

(with the light νs in the intermediate state)



Short range



According to the Schechter-Valle theorem, any mechanism inducing the $0\nu2\beta$ decay produces an effective Majorana mass for the neutrino, which must therefore contribute to this decay.

Purpose: to examine the possibility to discriminate among the various possible mechanisms contributing to the $0\nu2\beta$ decays using the information on the angular correlation of the final electrons.

Angular distribution

Most general Lorentz invariant effective Lagrangian for the long-range mechanism of $0\nu 2\beta$ decay:

$$L=\frac{G_F V_{ud}}{\sqrt{2}}\left\{\left(U_{ei}+\epsilon^{V-A}_{V-A,i}\right) j^{\mu i}_{V-A} J^{+}_{V-A,\mu}+\sum_{\alpha,\beta}{}^{'}\epsilon^{\beta}_{\alpha i}\, j^{i}_{\beta} J^{+}_{\alpha}+\mathrm{H.c.}\right\}$$

j & J are leptonic & hadronic currents of definite tensor structure and chirality; α,β=V $\pm$ A, S $\pm$ P, $T_{L,R}$; U_{ei} is PMNS mixing matrix; $\epsilon^{\beta}_{\alpha i}$ encode new physics.

- V+A currents (Doi M., Kotani T., Takasugi E. (1985))
- RPV MSSM (Hirsch M., Klapdor-Kleingrothaus H.V., Kovalenko S.G. (1996))
- Model with LQ (Hirsch M., Klapdor-Kleingrothaus H.V., Kovalenko S.G. (1996))

$$\epsilon^{V+A}_{V-A}=-\frac{\sqrt{2}}{2G_F}\left(\frac{\alpha_S^{(L)}}{M_S^2}+\frac{\alpha_V^{(L)}}{M_V^2}\right),\quad \epsilon^{V+A}_{V+A}=-\frac{\sqrt{2}}{4G_F}\left(\frac{\alpha_S^{(R)}}{M_S^2}+\frac{\alpha_V^{(R)}}{M_V^2}\right),\quad \epsilon^{S+P}_{S-P}=-\frac{\sqrt{2}}{4G_F}\frac{\epsilon_V}{M_V^2},\quad \epsilon^{S+P}_{S+P}=-\frac{\sqrt{2}}{4G_F}\frac{\epsilon_S}{M_S^2}.$$

$$\epsilon^{T_R}_{T_R,i}=\frac{1}{8}\eta^{n1}_{(q)LR}U^{*}_{ni}.$$

Approximations:

- leading order in the Fermi constant
- leading contribution of the parameters $\in$
- relativistic electrons and non-relativistic nucleons
- S_{1/2} and P_{1/2} waves for the outgoing electrons

Differential width on the cosθ for 0^+ to 0^+ transitions:

$$\frac{d\Gamma}{d\cos\theta} = \frac{\ln 2}{2}\left|M_{GT}\right|^2 \mathcal{A}(1-K\cos\theta), \qquad K = \frac{\mathcal{B}}{\mathcal{A}},$$

where θ is the angle between the electron momenta in the rest frame of the parent nucleus, M_{GT} is Gamov-Teller matrix element.

$\in$	$\mathcal{A}$
$\in^{V-A}_{V-A}$	$\mathcal{A}_0 + 4C_1 \lvert\mu\rvert \lvert\mu^{V-A}_{V-A}\rvert c_{02} + 4C_1 \lvert\mu^{V-A}_{V-A}\rvert^2$
$\in^{V-A}_{V+A}$	$\mathcal{A}_0 + 4C_0 \lvert\mu\rvert \lvert\mu^{V-A}_{V+A}\rvert c_{01} + 4C_{1+} \lvert\mu^{V-A}_{V+A}\rvert^2$
$\in^{V+A}_{V-A}$	$\mathcal{A}_0 + C_3 \lvert\mu\rvert \lvert\in^{V+A}_{V-A}\rvert c_2 + C_5 \lvert\in^{V+A}_{V-A}\rvert^2$
$\in^{V+A}_{V+A}$	$\mathcal{A}_0 + C_2 \lvert\mu\rvert \lvert\in^{V+A}_{V+A}\rvert c_1 + C_4 \lvert\in^{V+A}_{V+A}\rvert^2$
$\in^{S-P}_{S-P}$	$\mathcal{A}_0 + 4C^{SP}_0 \lvert\mu\rvert \lvert\mu^{S-P}_{S-P}\rvert c_{04} + 4C^{SP}_1 \lvert\mu^{S-P}_{S-P}\rvert^2$
$\in^{S-P}_{S+P}$	$\mathcal{A}_0 + 4C^{SP}_0 \lvert\mu\rvert \lvert\mu^{S-P}_{S+P}\rvert c_{03} + 4C^{SP}_1 \lvert\mu^{S-P}_{S+P}\rvert^2$
$\in^{S+P}_{S-P}$	$\mathcal{A}_0 + C^{SP}_2 \lvert\mu\rvert \lvert\in^{S+P}_{S-P}\rvert c_4 + C^{SP}_3 \lvert\in^{S+P}_{S-P}\rvert^2$
$\in^{S+P}_{S+P}$	$\mathcal{A}_0 + C^{SP}_2 \lvert\mu\rvert \lvert\in^{S+P}_{S+P}\rvert c_3 + C^{SP}_3 \lvert\in^{S+P}_{S+P}\rvert^2$
$\in^{T_L}_{T_L}$	$\mathcal{A}_0 + 4C^T_0 \lvert\mu\rvert \lvert\mu^{T_L}_{T_L}\rvert c_{06} + 4C^T_1 \lvert\mu^{T_L}_{T_L}\rvert^2$
$\in^{T_L}_{T_R}, \in^{T_R}_{T_L}$	$\mathcal{A}_0$
$\in^{T_R}_{T_R}$	$\mathcal{A}_0 + C^T_2 \lvert\mu\rvert \lvert\in^{T_R}_{T_R}\rvert c_5 + C^T_3 \lvert\in^{T_R}_{T_R}\rvert^2$

$\in$	$\mathcal{B}$
$\in^{V-A}_{V-A}$	$\mathcal{B}_0 + 4D_1 \lvert\mu\rvert \lvert\mu^{V-A}_{V-A}\rvert c_{02} + 4D_1 \lvert\mu^{V-A}_{V-A}\rvert^2$
$\in^{V-A}_{V+A}$	$\mathcal{B}_0 + 4D_0 \lvert\mu\rvert \lvert\mu^{V-A}_{V+A}\rvert c_{01} + 4D_{1+} \lvert\mu^{V-A}_{V+A}\rvert^2$
$\in^{V+A}_{V-A}$	$\mathcal{B}_0 + D_3 \lvert\mu\rvert \lvert\in^{V+A}_{V-A}\rvert c_2 + D_5 \lvert\in^{V+A}_{V-A}\rvert^2$
$\in^{V+A}_{V+A}$	$\mathcal{B}_0 + D_2 \lvert\mu\rvert \lvert\in^{V+A}_{V+A}\rvert c_1 + D_4 \lvert\in^{V+A}_{V+A}\rvert^2$
$\in^{S-P}_{S-P}$	$\mathcal{B}_0 + 4D_1^{SP} \lvert\mu^{S-P}_{S-P}\rvert^2$
$\in^{S-P}_{S+P}$	$\mathcal{B}_0 + 4D_1^{SP} \lvert\mu^{S-P}_{S+P}\rvert^2$
$\in^{S+P}_{S-P}$	$\mathcal{B}_0 + D_2^{SP} \lvert\mu\rvert \lvert\in^{S+P}_{S-P}\rvert c_4 + D_3^{SP} \lvert\in^{S+P}_{S-P}\rvert^2$
$\in^{S+P}_{S+P}$	$\mathcal{B}_0 + D_2^{SP} \lvert\mu\rvert \lvert\in^{S+P}_{S+P}\rvert c_3 + D_3^{SP} \lvert\in^{S+P}_{S+P}\rvert^2$
$\in^{T_L}_{T_L}$	$\mathcal{B}_0 + 4D_1^T \lvert\mu^{T_L}_{T_L}\rvert^2$
$\in^{T_L}_{T_R}, \in^{T_R}_{T_L}$	$\mathcal{B}_0$
$\in^{T_R}_{T_R}$	$\mathcal{B}_0 + D_2^T \lvert\mu\rvert \lvert\in^{T_R}_{T_R}\rvert c_5 + D_3^T \lvert\in^{T_R}_{T_R}\rvert^2$

In these tables:

$$\mu = \frac{\langle m \rangle}{m_e}, \quad \mu_\alpha^\beta = \frac{m_\alpha^\beta}{m_e}, \text{ with effective Majorana masses: } \langle \mathrm{m} \rangle = \sum_i U_{ei}^2 m_i,$$

$$m_{S\mp P}^{S-P} = \sum_i U_{ei} \in_{S\mp P,i}^{S-P} m_i, \quad m_{V\mp A}^{V-A} = \sum_i U_{ei} \in_{V\mp A,i}^{V-A} m_i, \quad m_{T_{L,R}}^{T_L} = \sum_i U_{ei} \in_{T_{L,R},i}^{T_L} m_i;$$

$$c_i = \cos\psi_i, \text{ with the relative phases: } \psi_{01} = \arg\left(\langle \mu \rangle \mu_{V+A}^{V-A*}\right), \psi_1 = \arg\left(\langle \mu \rangle \in_{V+A}^{V+A*}\right)\ldots$$

$$\mathcal{A}_0 = C_1 |\mu|^2, \quad \mathcal{B}_0 = D_1 |\mu|^2.$$

The quantities C_i, $C_i^{(SP,T)}$, D_i and $D_i^{(SP,T)}$ are expressed through the intergated phase space factors A_{0k}, $A_{0k}^{(SP,T)}$, B_{0k}, $B_{0k}^{(SP,T)}$ and the combinations of nuclear parameters.

The expressions associated with the coefficients $\in_{V\mp A}^{V+A}$ confirm the results of Doi et al. (1985), while the expressions associated with the other coefficients $\in_\alpha^\beta$ transcend the earlier work.

The integrated kinematic A- and B-factors [in $10^{-15}\,\mathrm{yr}^{-1}$]
for the $0^+ \rightarrow 0^+$ transition of the $0\nu 2\beta$ decay of ^{76}Ge.

A_{01}	6.69	B_{01}	5.45
A_{02}	1.09×10	B_{02}	8.95
A_{03}	3.76	B_{03}	–
A_{04}	1.30	B_{04}	1.21
A_{05}	2.08×10^{2}	B_{05}	7.27
A_{06}	1.69×10^{3}	–	–
A_{07}	1.46×10^{5}	B_{07}	7.72×10^{4}
A_{08}	6.59×10^{3}	B_{08}	4.97×10^{3}
A_{09}	4.15×10^{5}	B_{09}	3.00×10^{5}

A_{00}^{SP}	2.55	–	–
A_{01}^{SP}	3.77	B_{01}^{SP}	2.73
A_{02}^{SP}	1.18×10^{-1}	B_{02}^{SP}	7.20×10^{-2}
A_{03}^{SP}	1.27×10^{-3}	B_{03}^{SP}	3.71×10^{-4}
A_{01}^{T}	6.03×10	B_{01}^{T}	4.36×10
A_{02}^{T}	1.50×10^{3}	B_{02}^{T}	1.40×10^{3}
A_{03}^{T}	7.67×10^{5}	B_{03}^{T}	7.16×10^{5}

Analysis of the electron angular correlation

If the ``nonstandard" effects, are zero then K = B01/A01. Its values are given in the Table for various decaying nuclei of current experimental interest:

	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
K	0.82	0.88	0.88	0.85	0.85

The presence of the ``nonstandard" parameters $\in^{V-A}_{V\mp A}$, $\in^{S+P}_{S\mp P}$, $\in^{T_L}_{T_R}$ or $\in^{T_R}_{T_L}$ does not change significantly the form of the angular correlation.

The presence of the ``nonstandard" parameters $\in^{V+A}_{V\mp A}$, $\in^{S-P}_{S\mp P}$, $\in^{T_L}_{T_L}$ or $\in^{T_R}_{T_R}$ does change this correlation.

The angular correlation coefficient K for various SM extensions for decays of ^{76}Ge.

SM extension	$\{\in\}$	K
ν_M	$-$	0.82
ν_M + RPV SUSY	$\in^{T_R}_{T_R}$	$(-1; 1)$
ν_M + RC	$\in^{V+A}_{V\mp A}$	$(-1; 1)$

Particular cases for the parameter space

1. $|\langle m \rangle| = 0$: $\quad T_{1/2} = \ln 2/\Gamma = \left(|M_{GT}|^2 \mathcal{A}\right)^{-1}$

For the lower bound $T_{1/2} > 1.2\times10^{25}$ yr the conservative upper bounds are:

$\left|\mu^{V-A}_{V-A}\right|$	$\left|\mu^{V-A}_{V+A}\right|$	$\left|\in^{V+A}_{V-A}\right|$	$\left|\in^{V+A}_{V+A}\right|$
$5.8(13)\times10^{-7}$	$6.1(7.5)\times10^{-7}$	$2.5(6.0)\times10^{-11}$	$9.3(28)\times10^{-7}$

Constraints on the couplings of the effective LQ-quark-lepton interactions:

$$\left|\alpha_I^{(L)}\right| \le 5.8\times10^{-12}\left(\frac{M_I}{100\text{ GeV}}\right)^2, \quad \left|\alpha_I^{(R)}\right| \le 3.0\times10^{-7}\left(\frac{M_I}{100\text{ GeV}}\right)^2, \quad I = S, V.$$

$T_{1/2}$ and K for the fixed values of the parameters $|\mu^{V\text{-}A}_{V\mp A}|=|\in^{V+A}_{V+A}|=5\times10^{-7}$, $|\in^{V+A}_{V-A}|=10^{-11}$ for decay of ^{76}Ge for the case of $|\langle m\rangle|=0$ in QRPA without (with) p-n pairing.

	$\left\|\mu^{V-A}_{V-A}\right\|$	$\left\|\mu^{V-A}_{V+A}\right\|$	$\left\|\in^{V+A}_{V-A}\right\|$	$\left\|\in^{V+A}_{V+A}\right\|$
$T_{1/2}/(10^{25}\,\text{yr})$	1.6(8.3)	1.8(2.7)	7.5(42)	4.0(39)
K	0.82(0.82)	0.82(0.82)	–0.72(–0.73)	–0.79(–0.87)

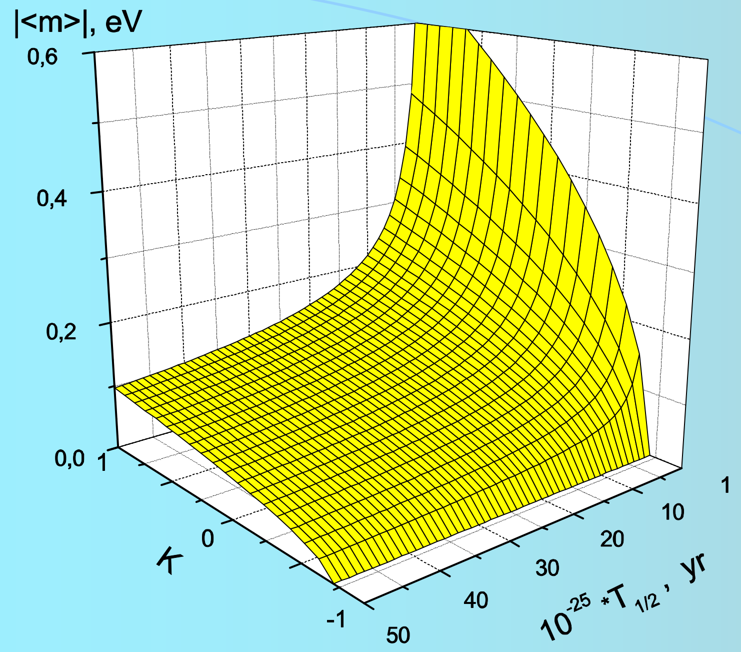
2. $|\langle m\rangle|\neq 0$, $\cos\psi_i=0$:

for $\in^{V+A}_{V+A}\neq 0$

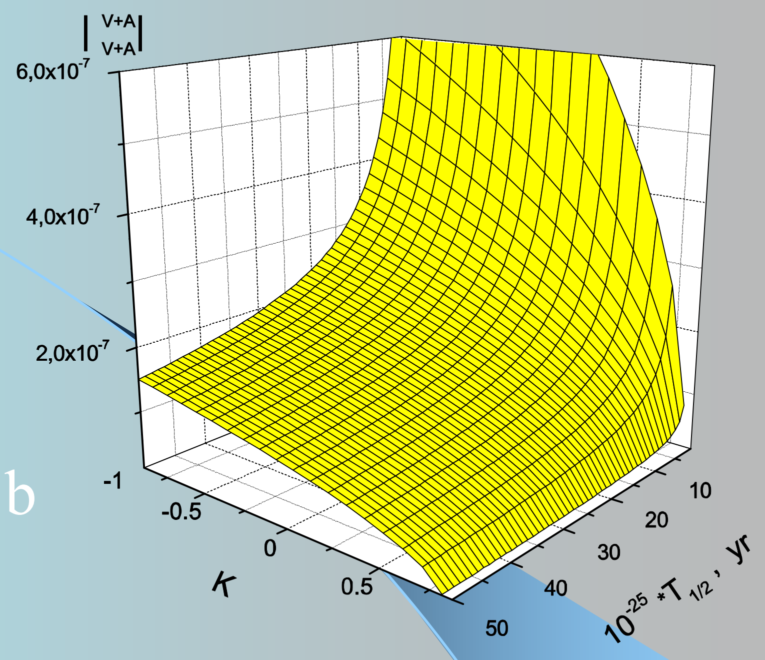
$$|\mu|^2=(7.9+10K)\times10^{12}/T_{1/2},\quad \left|\in^{V+A}_{V+A}\right|^2=(5.1-6.3K)\times10^{12}/T_{1/2}$$

for $\in^{V+A}_{V-A}\neq 0$

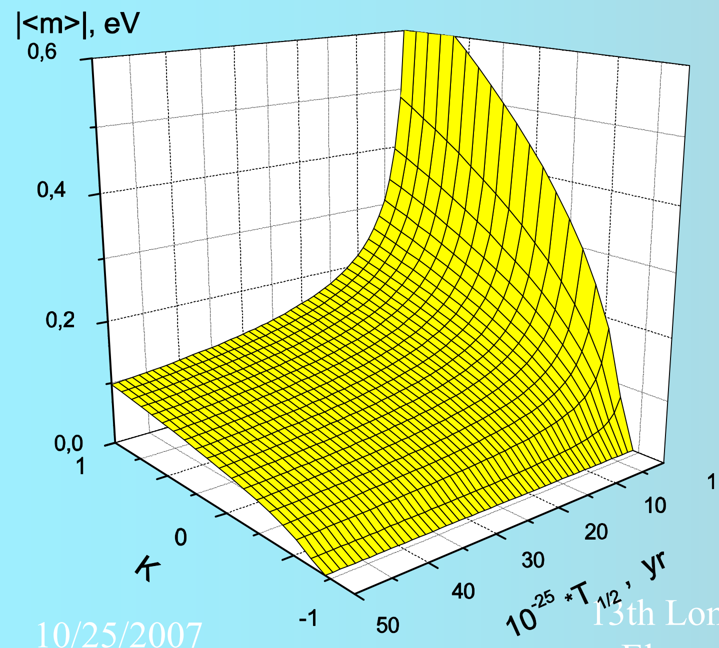
$$|\mu|^2=(7.6+10.5K)\times10^{12}/T_{1/2},\quad \left|\in^{V+A}_{V-A}\right|^2=(4.0-4.9K)\times10^{12}/T_{1/2}.$$


|<m>|, eV
0,6
0,4
0,2
0,0
1
0
-1
K
1
10
20
30
40
50
10^-25 *T 1/2 , yr

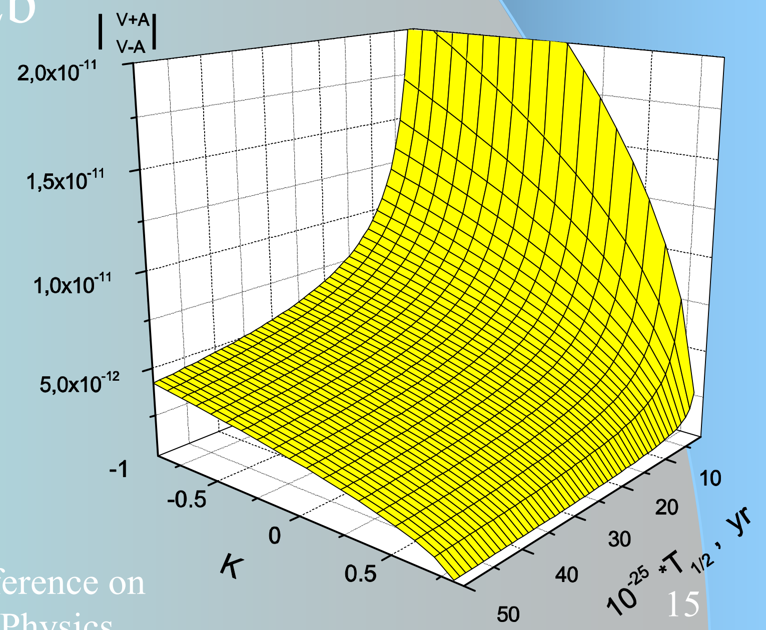
1a


| V+A V+A |
6,0x10^-7
4,0x10^-7
2,0x10^-7
-1
-0.5
0
0.5
K
10
20
30
40
50
10^-25 *T 1/2 , yr

1b


|<m>|, eV
0,6
0,4
0,2
0,0
1
0
-1
K
1
10
20
30
40
50
10^-25 *T 1/2 , yr

2a


| V+A V-A |
2,0x10^-11
1,5x10^-11
1,0x10^-11
5,0x10^-12
-1
-0.5
0
0.5
K
10
20
30
40
50
10^-25 *T 1/2 , yr

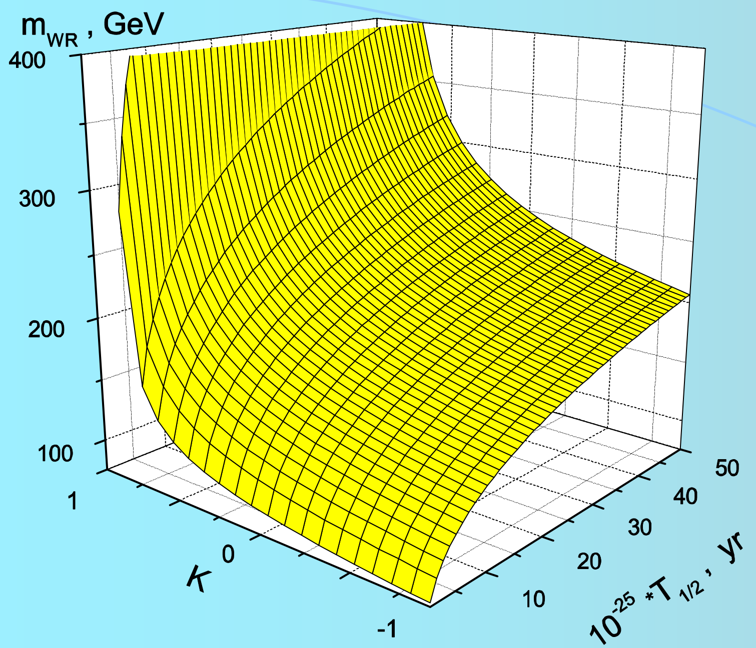
2b

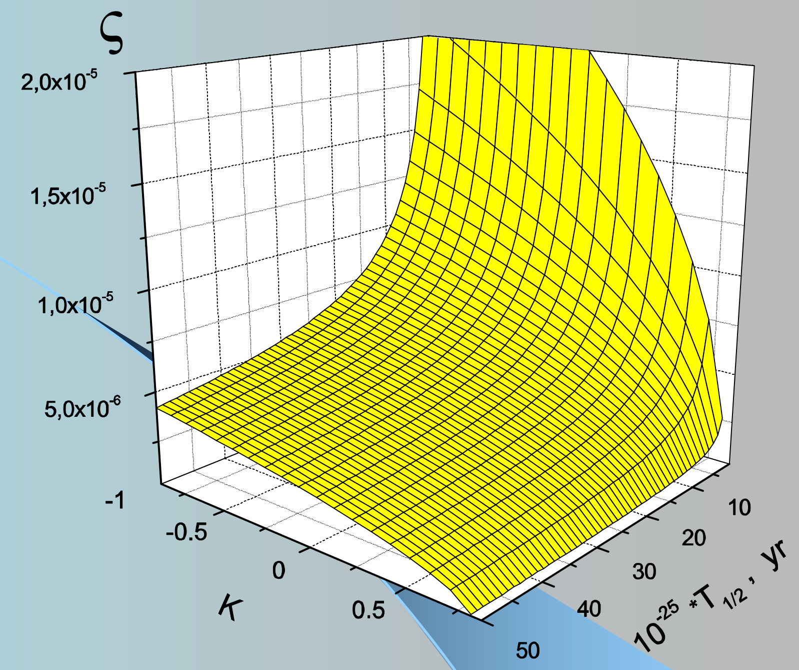
Angular correlation in left-right symmetric models

For the model $SU(2)_L \times SU(2)_R \times U(1)$ using the condition $m_{W_L} << m_{W_R}$:

$$m_{W_R} = m_{W_L} \sqrt{\frac{\in}{\left|\in_{V+A}^{V+A}\right|}}, \quad \varsigma = -\arctan\left(\left|\in_{V-A}^{V+A}\right| / \in\right), \quad \text{with} \ \in = \left|U_{ei} V_{ei}\right|.$$

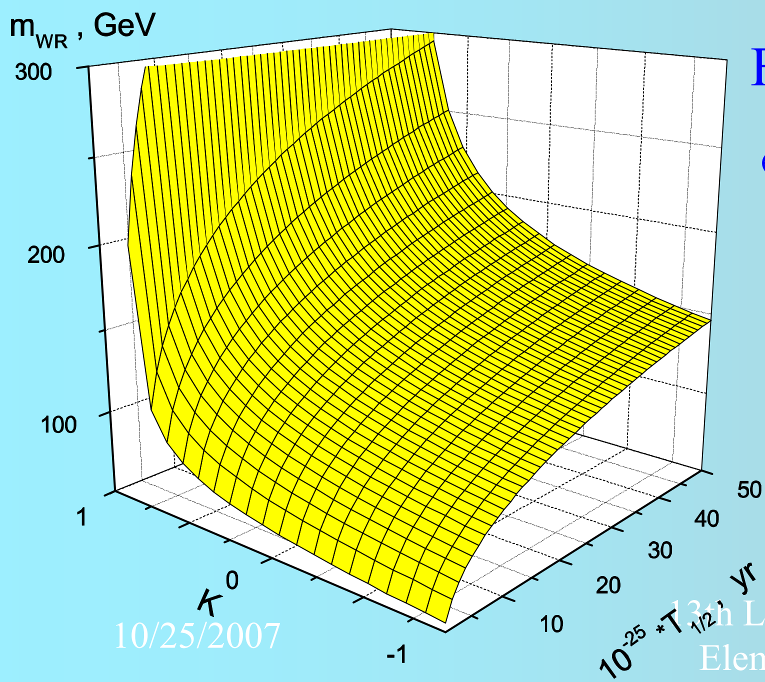
Using $m_{W_L} \approx m_{W_1} = 80.4$ GeV for the values $\in = 10^{-6}$, 5×10^{-7} we have got the correlation shown in Figs 3, 4.

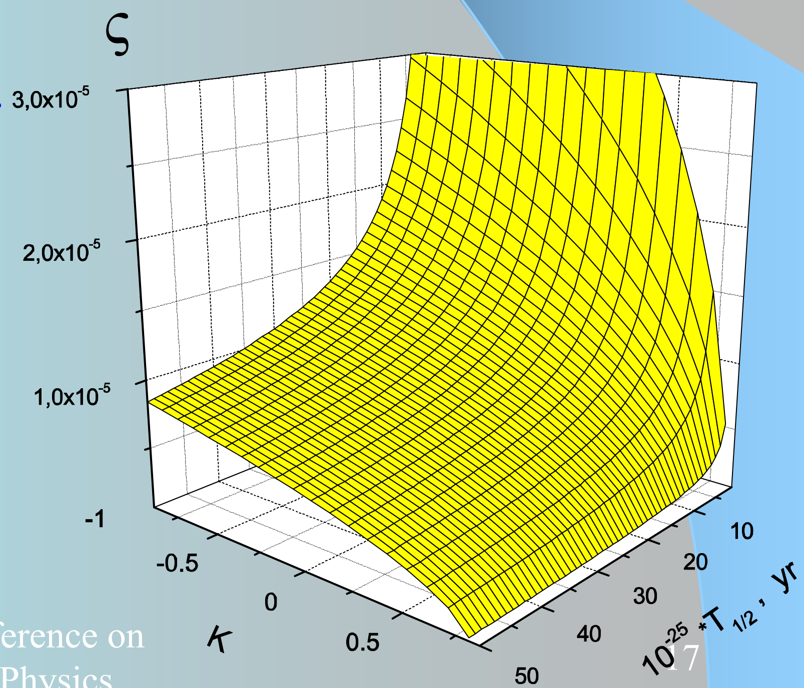




Figs 3a, 3b.

$\in = 10^{-6}$





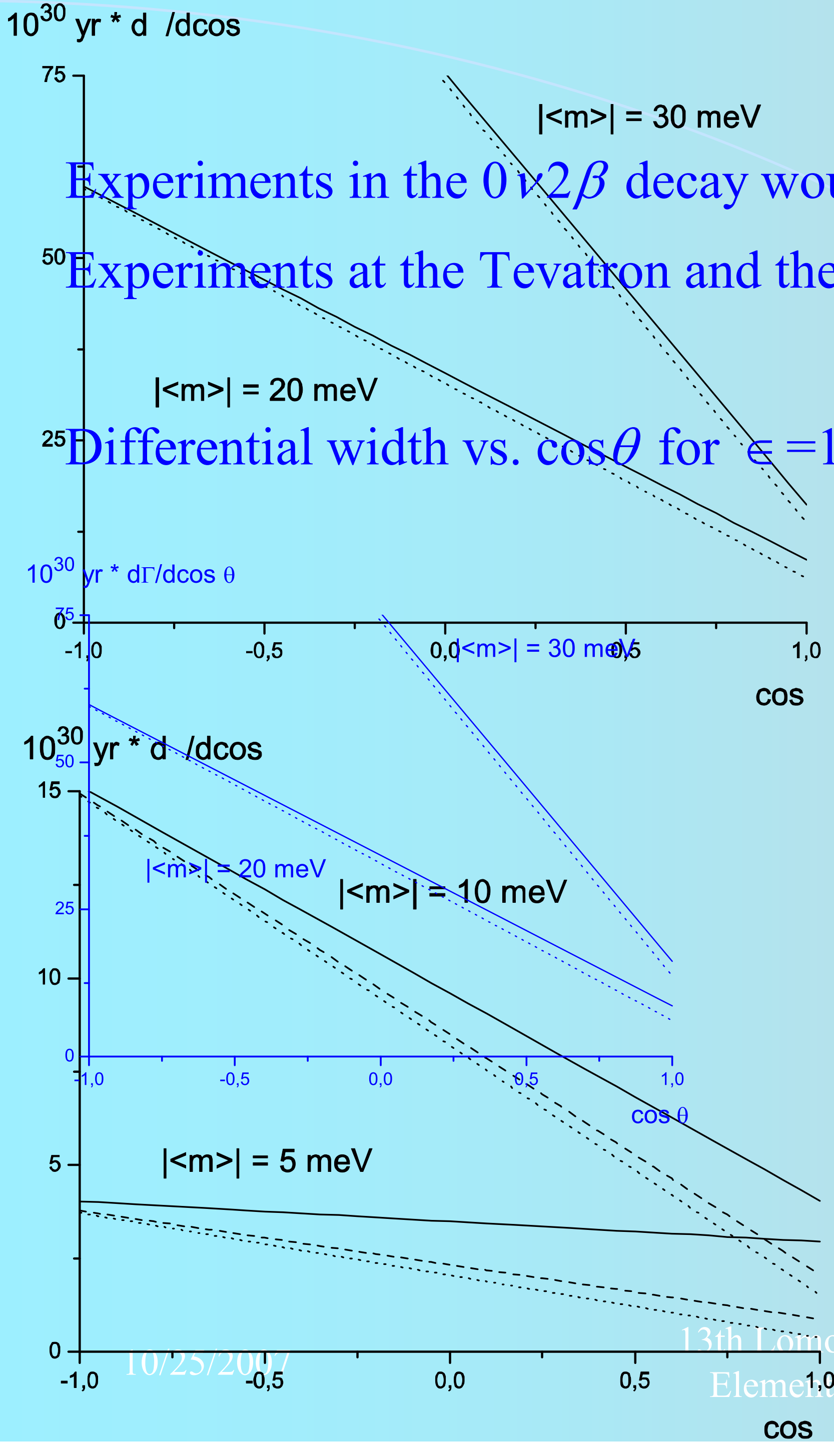
Figs 4a, 4b.

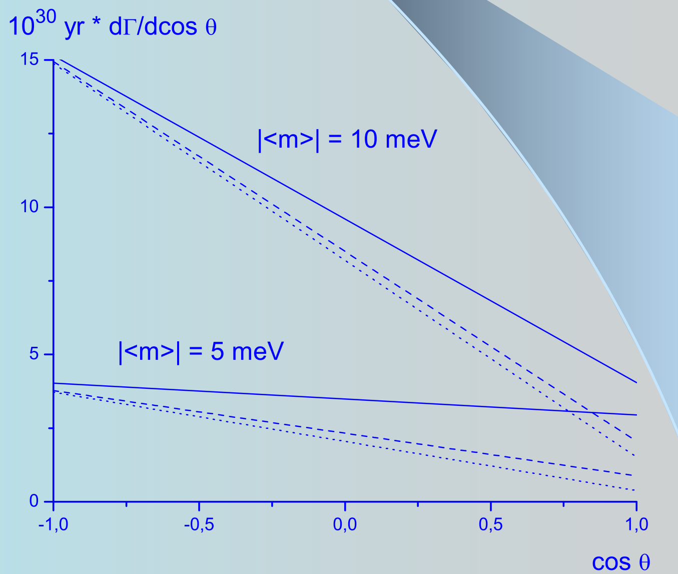
$\in = 5\times10^{-7}$

Experiments in the $0\nu2\beta$ decay would measure m_{W_L}/m_{W_R} and $U_{ei}V_{ei}$.

Experiments at the Tevatron and the LHC can measure m_{W_L}/m_{W_R}.

Differential width vs. $\cos\theta$ for $\epsilon = 10^{-6}$:





Conclusion

- We have presented a detailed study of the electron angular correlation for the long range mechanism of $0\nu2\beta$ decays in a general theoretical context. This information, together with the ability of observing these decays in several nuclei, would help greatly in identifying the dominant mechanism underlying these decays.

- The proposed experimental facilities that in principle can measure the electron angular correlation in the $0\nu2\beta$ decays are NEMO3, ELEGANT V and some others. There is a strong case in building at least one of them.