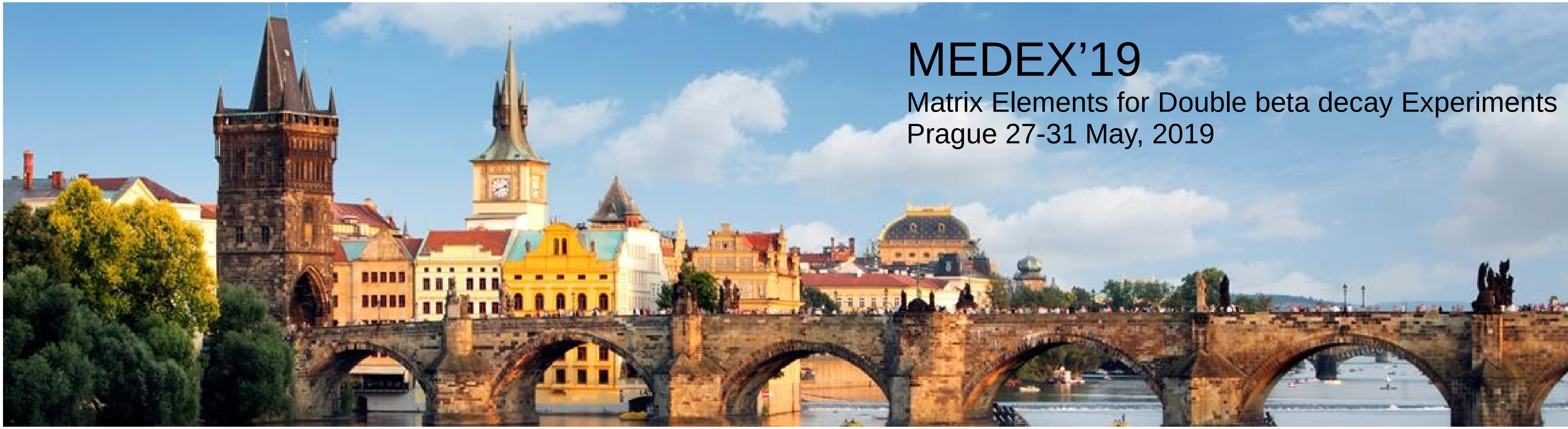
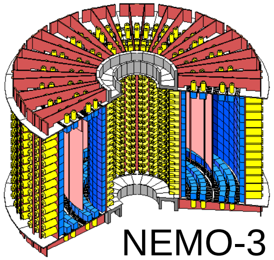
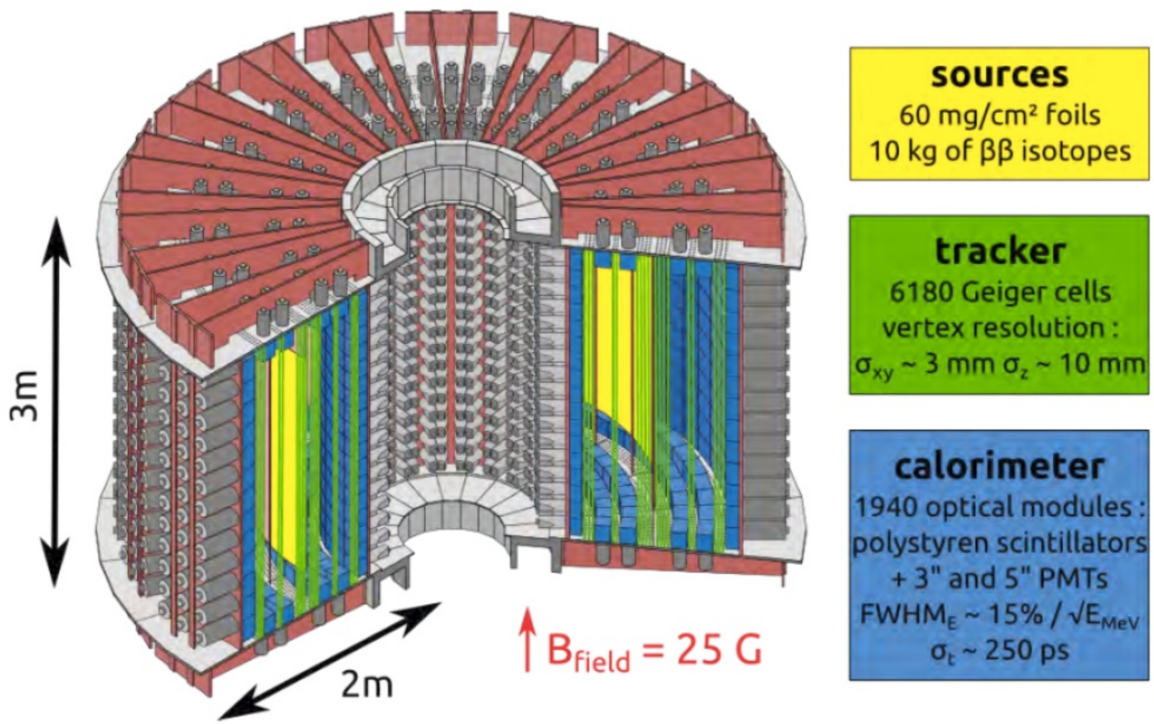


Investigation of Mo-100 two-neutrino double beta decay in NEMO-3

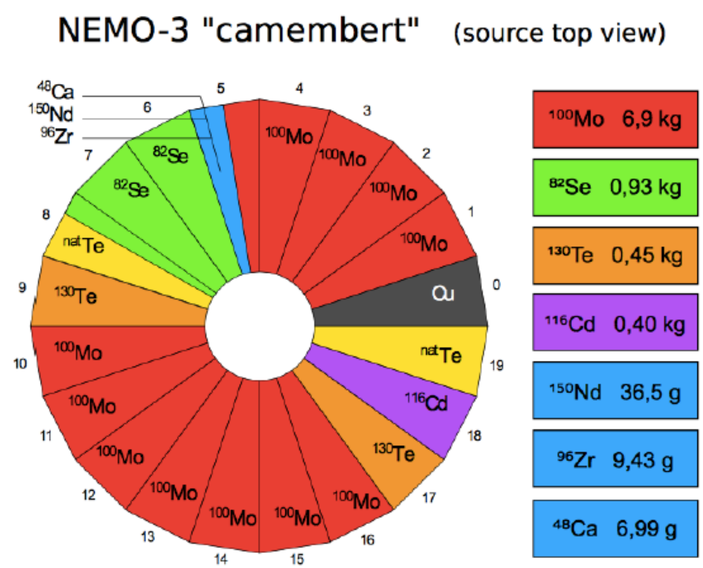
Victor Tretyak
JINR, Dubna
On behalf of NEMO-3 collaboration



NEMO-3 detector



NEMO-3 (2003-2011)



- Source separated from detector
- Full topological reconstruction, particle identification
- Powerful background suppression
- Ability to discriminate different transition mechanisms
- Modular

Experimental Data

The data presented here were collected between February 2003 and October 2010 with a live time of 4.96 y and a total exposure of 34.3 kg·y of ^{100}Mo.

The ^{100}Mo $0\nu\beta\beta$ decay results produced with this data was published in *Phys. Rev. D 92, 072011 (2015)* :

$$T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y (90\% C.L.)}$$

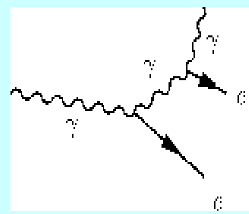
Two types of purified molybdenum foils were installed in NEMO-3, metallic and composite. Both foil types were enriched in ^{100}Mo with the isotopic enrichment factor ranging from 95.14 ± 0.05% to 98.95 ± 0.05%. The average enrichment factor was 97.7% for metallic foils and 96.5% for composite foils.
The metallic foils contained 2479 ± 5 g of ^{100}Mo.
The composite foils contained 4435 ± 13 g of ^{100}Mo

NEMO-3 backgrounds

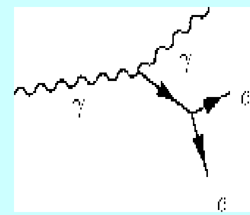
Source of background:
- Natural radioactivity outside and inside source foils:
  - ^{238}U / ^{232}Th chains
  - ^{40}K
  - Rn
- cosmic μ
- neutrons

NEMO-3 measures each component of background using events of different topology:
eα, crossing electron, eγ-external, e(N)γ-internal, single electron

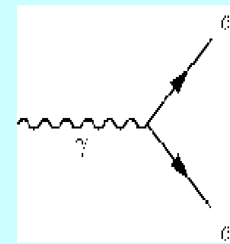
External



double Compton

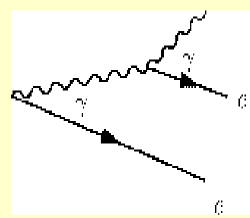


Compton + Moller

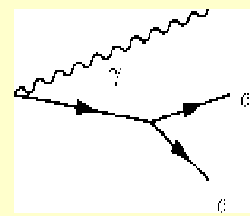


pair production

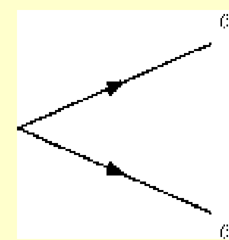
Internal



β^-+Compton



β^-+Moller



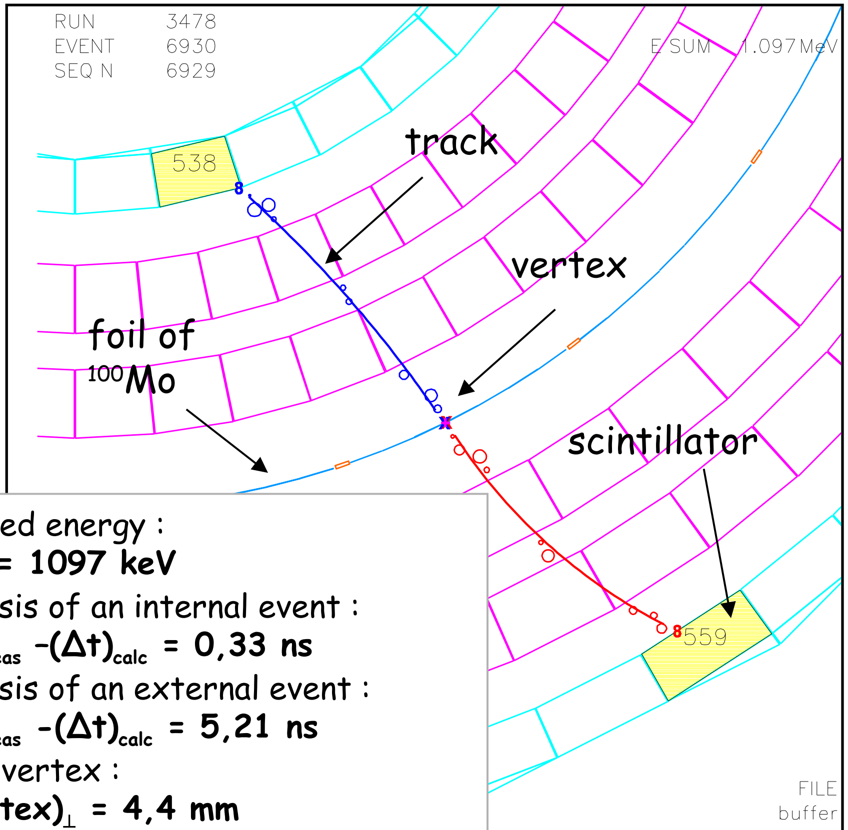
β^-+IC

Background measurement in NEMO-3: *NIM A606, 449 (2009); Phys. Rev. D 92, 072011 (2015)*

Selection of ββ events

The example of the typical ββ event - candidate for ββ2ν decay of ^{100}Mo

Top view

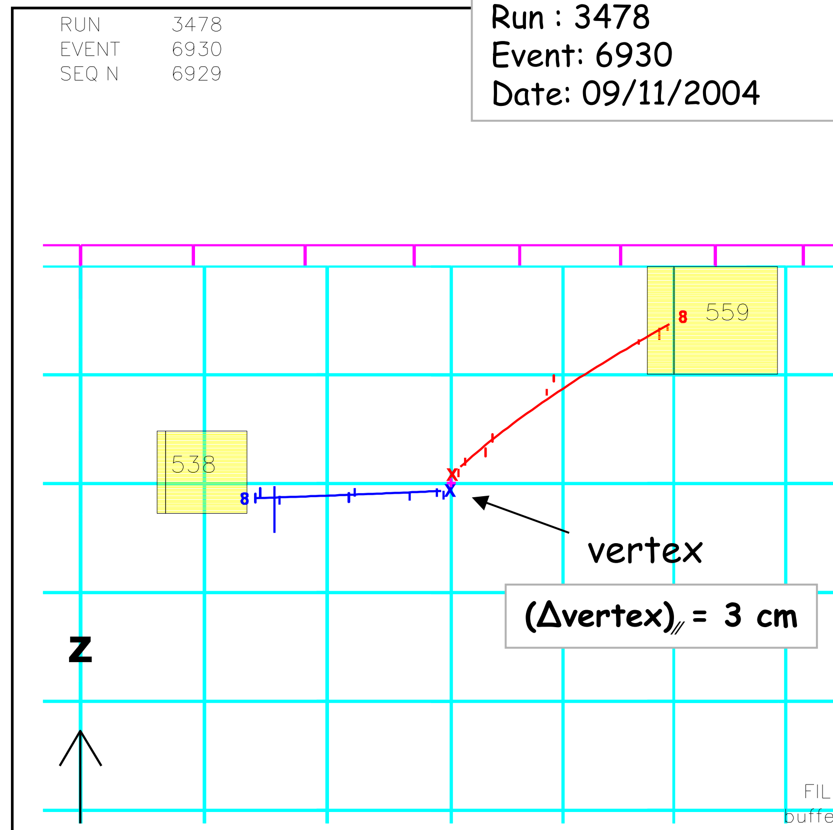


Registered energy :
E_1+E_2= 1097 keV
Hypothesis of an internal event :
$(\Delta t)_{meas} - (\Delta t)_{calc}$ = 0,33 ns
Hypothesis of an external event :
$(\Delta t)_{meas} - (\Delta t)_{calc}$ = 5,21 ns
Common vertex :
$(\Delta vertex)_{\perp}$ = 4,4 mm

1 ββ event each 2,5 minutes

Side view

Run : 3478
Event: 6930
Date: 09/11/2004



$(\Delta vertex)_{//}$ = 3 cm

Criteria to select ββ events:

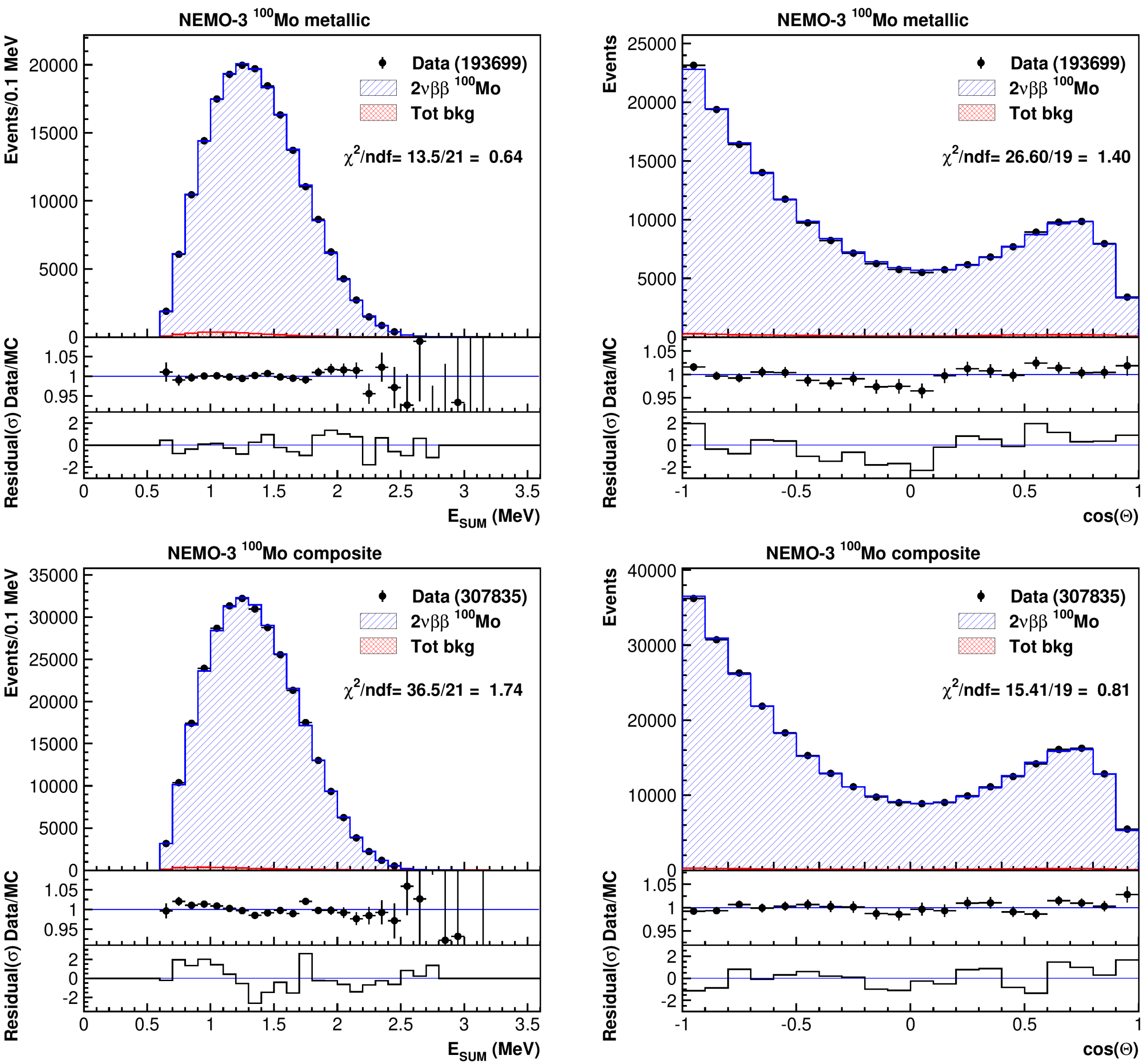
- 2 tracks with curvature < 0
- 2 PMT, each > 300 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)
- PMT gain stability from laser survey

Number of selected events background estimation and 2νββ signal

Source	Metal	Composite	Total ^{100}Mo
^{228}Ac, ^{212}Bi, ^{208}Tl	49.5 ± 0.5	142.3 ± 1.3	191.8 ± 1.4
^{214}Pb, ^{214}Bi	14.2 ± 0.1	177.2 ± 0.7	191.3 ± 0.7
^{40}K	101.4 ± 2.5	296.0 ± 7.3	397.5 ± 7.7
^{234m}Pa	1783.8 ± 11.8	656.7 ± 4.3	2440.5 ± 12.5
^{210}Bi	25.6 ± 1.4	90.3 ± 2.8	115.9 ± 3.1
Radon	434.3 ± 6.2	590.3 ± 5.2	1024.6 ± 8.1
Ext Bkg	562.7 ± 9.7	1238.6 ± 14.7	1801.3 ± 17.6
$\beta\beta\ 0_1^+$	48.6 ± 0.8	71.1 ± 1.0	119.7 ± 1.3
Tot bkg	3020 ± 17	3263 ± 18	6283 ± 25
$\beta\beta$ g.s.	190683 ± 117	304571 ± 144	495254 ± 186
Data	193699	307835	501534

Number of ^{100}Mo 2νββ events for the decay to the ground state of ^{100}Ru is obtained from log-likelihood fit of the two-electron energy sum distribution

Metallic and composite foils separately



Metallic foils

$T_{1/2} = (6.65 \pm 0.02) \times 10^{18}$ y

S/B = 63

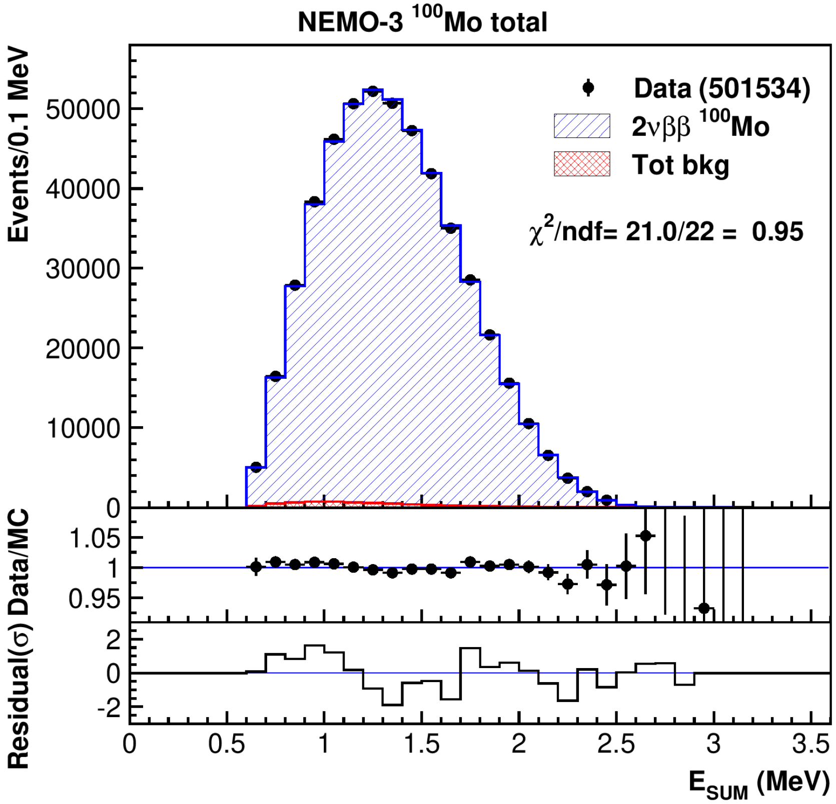
Composite foils

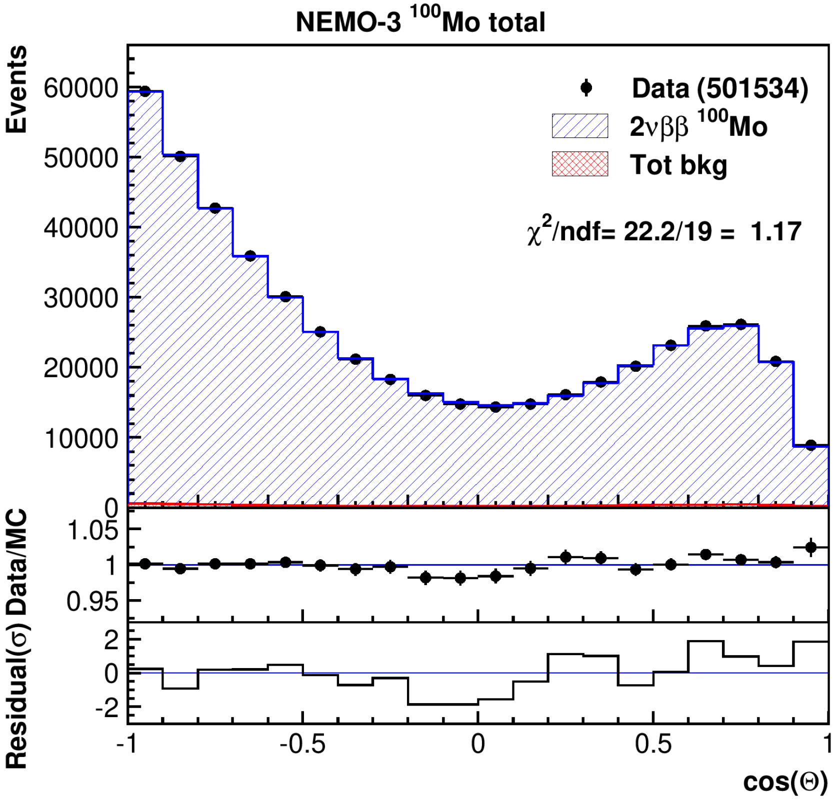
$T_{1/2} = (6.91 \pm 0.01) \times 10^{18}$ y

S/B = 94

The difference between the two sample measurements may be explained by inaccuracy of the thin foil modelling and is taken into account in estimation of the systematic uncertainty. The mean value over the two data samples is considered to give the more reliable half-life estimation.

Total ^{100}Mo data sample





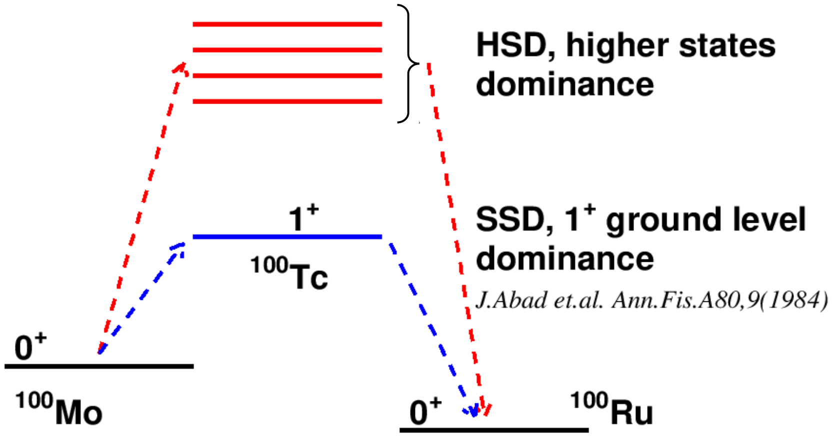
The ^{100}Mo $2\nu\beta\beta$ half life $T_{1/2} = (6.81 \pm 0.01) \times 10^{18}$ y , S/B =79

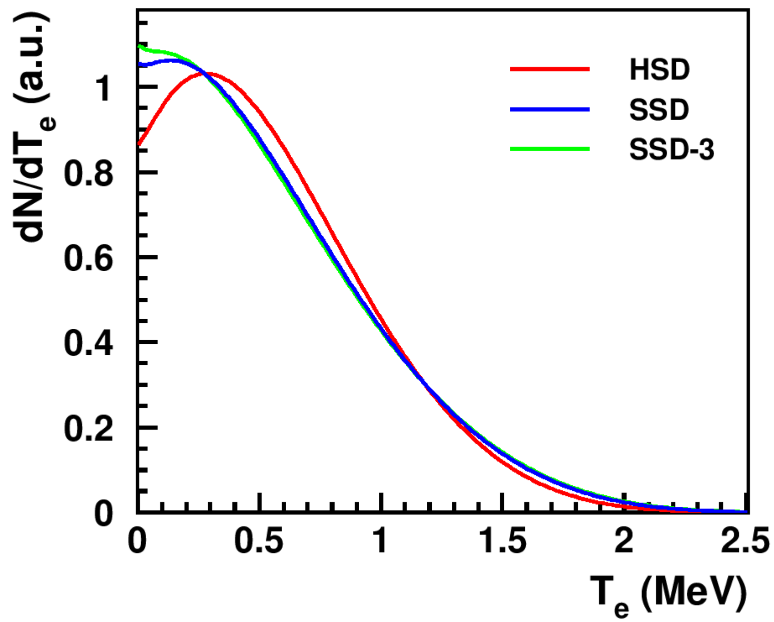
This result is obtained for SSD model

Single State Dominance vs Higher State Dominance

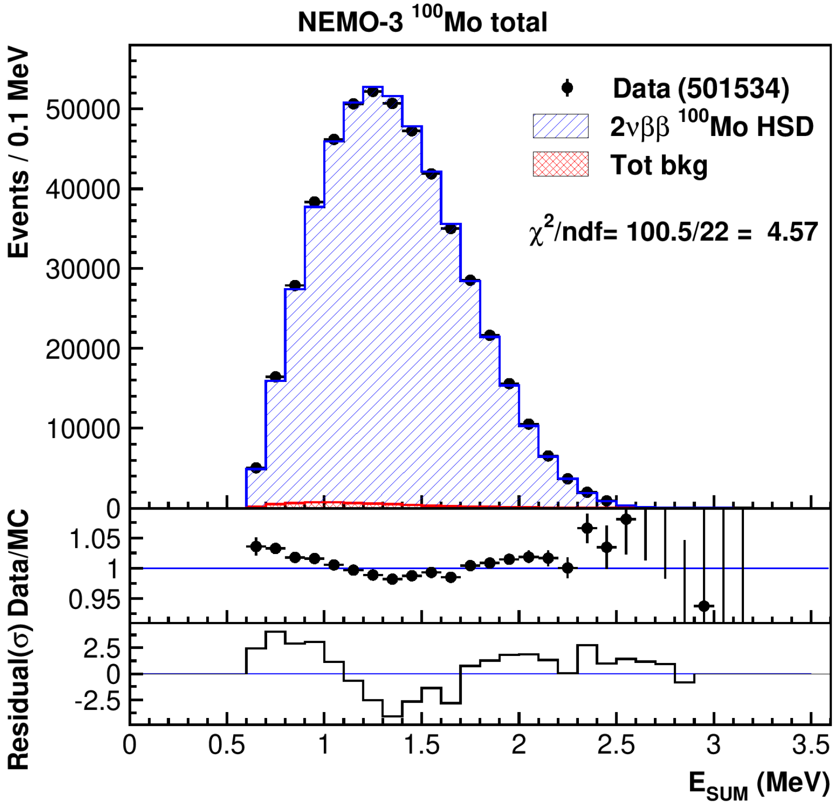
It was shown in
F. Šimkovic et al., J. Phys. G 27, 2233 (2001);
P. Domin, S. Kovalenko, F. Šimkovic, S.V. Semenov, Nucl. Phys. A 753, 337 (2005)
that SSD and HSD models can be directly distinguished by making high precision kinematics measurements of 2νββ decay products.
The distribution of the individual electron energies was shown to have the most discriminating power.

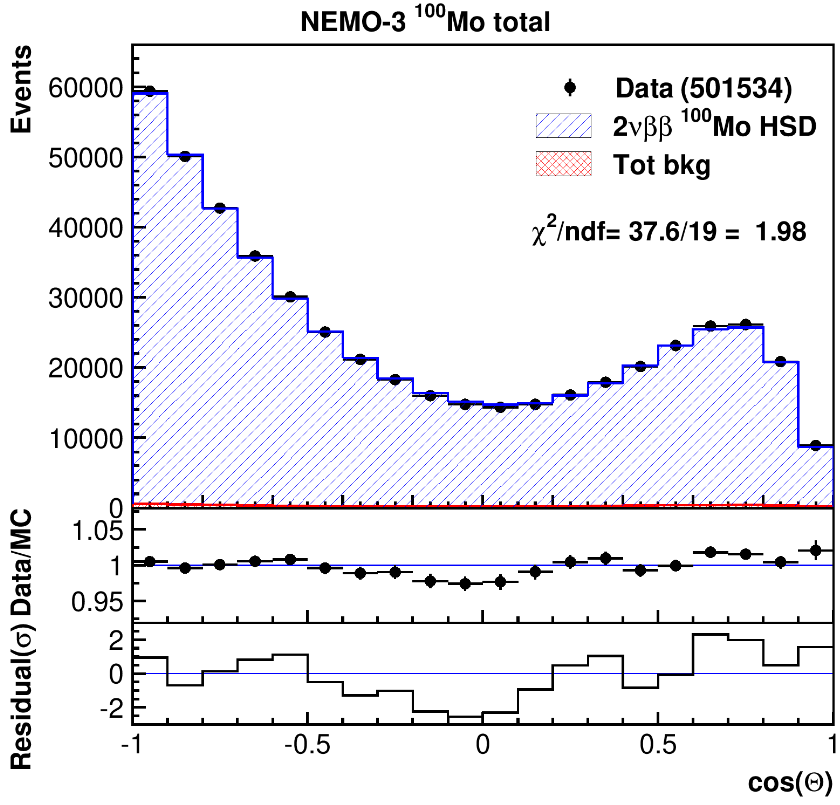
SSD-3 model is also considered, being a modification of the SSD model where excited 1^+ states are accounted for in addition to the ground state of the intermediate nucleus ^{100}Tc
S.V. Semenov, Phys. Part. Nuclei 48, 1018 (2017)





Fit result for HSD model

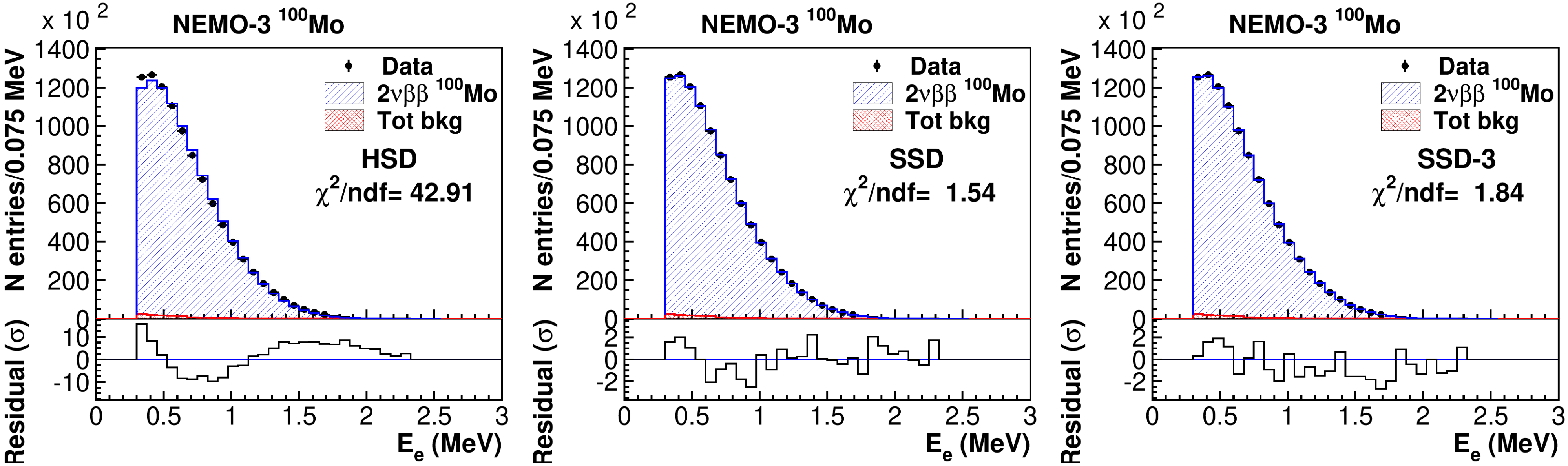




The tension between the data and the model is evident already from these distributions with χ^2/ndf=4.57 (p-value=$5.3 \cdot 10^{-12}$) for the energy sum and χ^2/ndf=1.98 (p-value=0.007) for angular distribution.

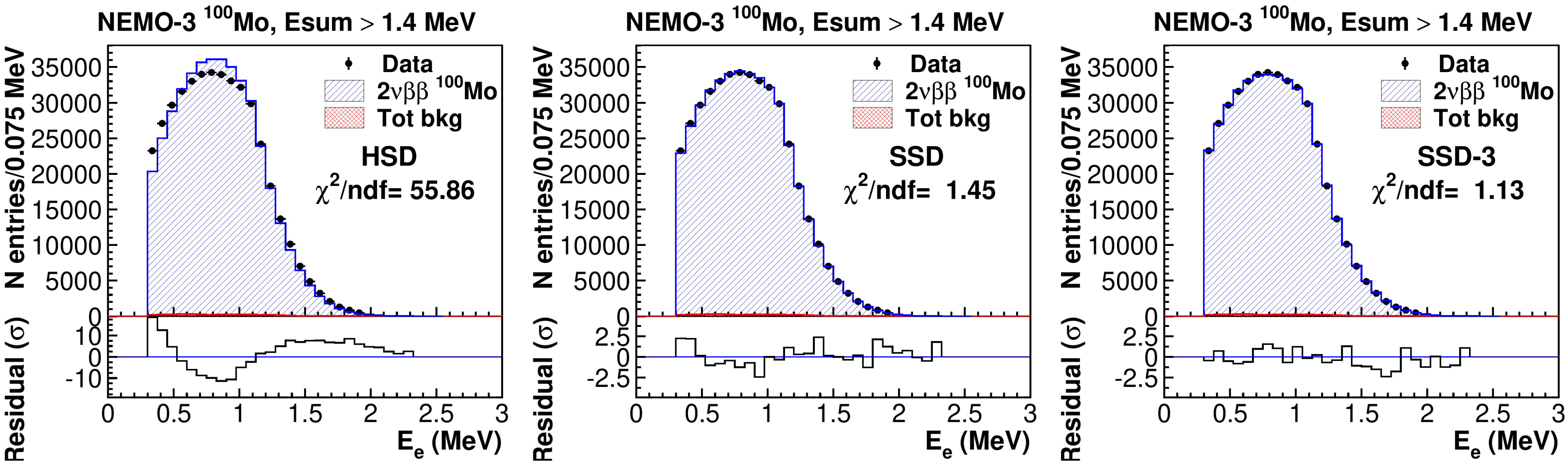
However, the single electron energy distribution has much higher discriminating power.

Single electron energy for HSD, SSD and SSD-3



It is clear from the distributions and χ^2 values that the HSD model can be ruled out with high confidence while SSD and SSD-3 provide a fairly good description of the data. The χ^2 value is smaller for SSD.

Single electron energy for E_{SUM} > 1.4 MeV



The cut E_{SUM} > 1.4 MeV maximizes the difference between SSD and SSD-3 and also increases the signal-to-background ratio.

The χ^2 value is smaller for SSD-3 than for SSD contrary to the results at the previous slide.

Due to systematic effects connected to the energy reconstruction and electron energy loss simulations these two models cannot be discriminated against each other.

The SSD is chosen as the baseline model and is used to estimate the ^{100}Mo 2νββ half-life.

The SSD-3 model would give a 1.8% shorter half-life than that of the SSD model. This difference is accounted for in the estimation of the half-life systematic uncertainty

Systematic uncertainties on ^{100}Mo $2\nu\beta\beta$ half-life

Source of uncertainty	Effect on $T_{1/2}$ (%)
Absolute normalization of ε_{2e}	± 5
Thin source foil modelling	[+ 1.5, – 2.3]
^{100}Mo decay model	± 1.8
Energy calibration	± 0.6
^{100}Mo mass	± 0.2
Background uncertainty	± 0.2
Total	[+ 5.6, - 5.8]

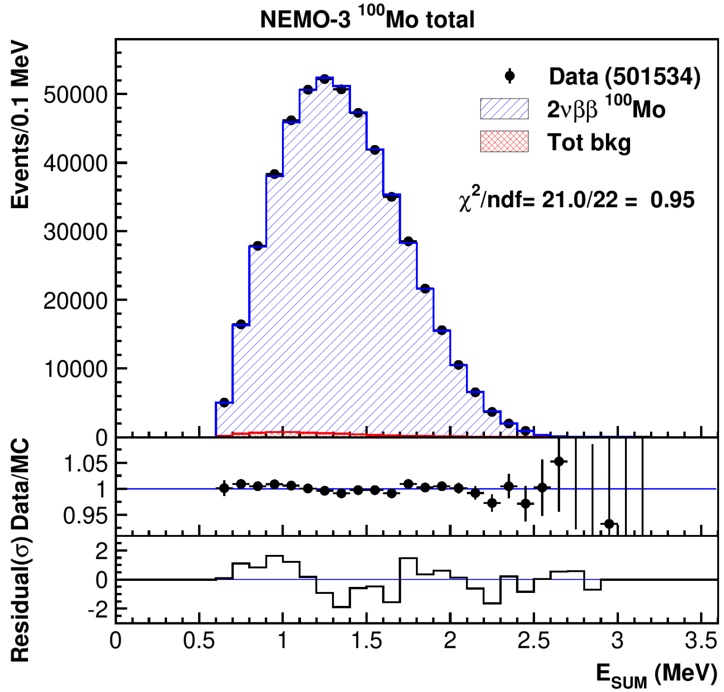
The final value of the half-life for the $2\nu\beta\beta$ decay of ^{100}Mo under the SSD model is:

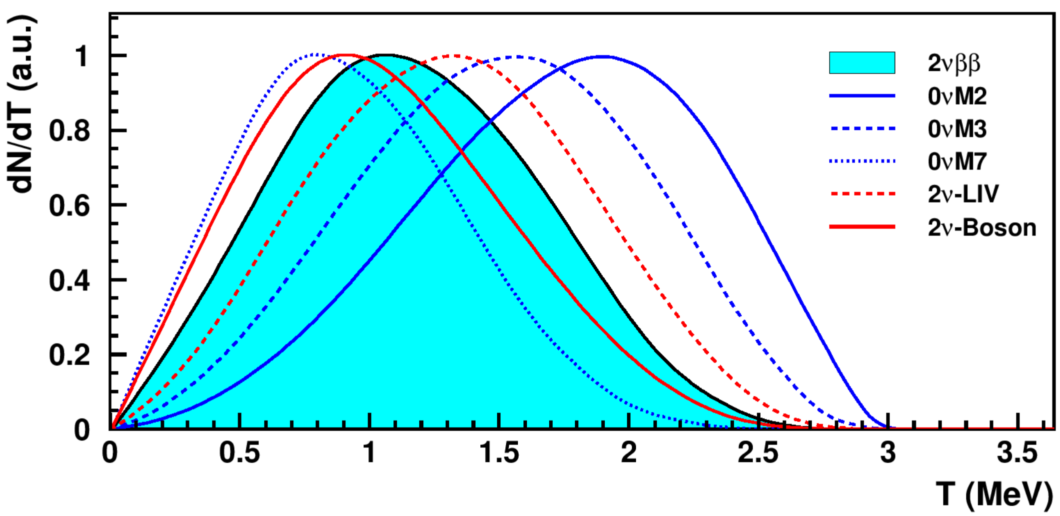
$T_{1/2}$ = [6.81 ± 0.01 (stat) +0.38−0.40 (syst)] × 10^{18} y

This is in good agreement with the world average value of
$T_{1/2} = (7.1 \pm 0.4) \times 10^{18}$ y *A. Barabash, Nucl. Phys. A 935, 52 (2015)*
and with a recent result obtained using $Li_2{}^{100}MoO_4$ bolometers:
$T_{1/2}$ = [6.90±0.15(stat)±0.37(syst)]×10 y *E. Armengaud et al., Eur. Phys. J. C 77, 785 (2017)*

Limits set with energy sum distribution

Deviations in the shape of the 2νββ energy spectra can provide hints of new physics.





$dN/dT \sim (Q_{\beta\beta}-T)^n$, where n - spectral index

The full energy sum distribution for the full ^{100}Mo data set is used.
The ordinary 2νββ decay corresponds to the spectral index n=5
We have considered contributions from 0νββ decay with Majoron emission for n=2,3,7;
the 2νββ decay with bosonic neutrino n=6;
the effect in 2νββ decay due to Lorentz invariance violation n=4.

Limits on $0\nu\beta\beta$ decay accompanied by Majoron emission

The half-life limit on $0\nu\beta\beta$ decay accompanied by Majoron emission with spectral index n=1 $T_{1/2} > 4.4 \times 10^{22}$ y (90% C.L.) is published in NEMO-3 paper *Phys. Rev. D 92, 072011 (2015)*

Here we consider Majoron-accompanied $0\nu\beta\beta$ decay modes with spectral indices n=2,3,7:

$0\nu\beta\beta\,\chi^0$ with n=2,3
$0\nu\beta\beta\,\chi^0\chi^0$ with n=3,7

The 90% C.L. half-life limits set with CL_s method (COLLIE)

Decay mode	$T_{1/2}$ ($\times 10^{21}$ y)
Majoron n=2	9.9
Majoron n=3	4.4
Majoron n=7	1.2
$2\nu\beta\beta$ Bosonic ν n=6	1.2

Upper limits on the Majoron-neutrino coupling constant $\langle g_{ee} \rangle$, 90% C.L.

n	Mode	^{100}Mo *	^{136}Xe	^{76}Ge
3	χ^0	0.013 - 0.035	0.06	0.47
3	$\chi^0\chi^0$	0.59 – 5.9	0.6 – 5.5	0.7 – 6.6
7	$\chi^0\chi^0$	0.48 – 4.8	0.04 – 4.7	0.8 – 7.1

* NME,PSF: *M.Hirsch et al., Phys.Lett.B 372, 8 (1996)*
C.Barbero et al., Phys.Lett. B 392, 419 (1997)
^{136}Xe: *J. B. Albert et al., Phys. Rev. D 90, 092004 (2014)*
^{76}Ge: *M. Agostini, et al., Eur. Phys. J. C 75, 416 (2015)*

Limit on bosonic neutrino contribution

The bosonic component in the neutrino states considered in *A.S. Barabash et al., Nucl. Phys. B 783, 90 (2007)* would provide the energy sum distribution corresponding to index n=6. The total 2νββ-decay probability with fermionic and bosonic neutrinos can be parametrised as

$$W_{tot} = \cos^4\chi\ W_f + \sin^4\chi\ W_b$$

Using theoretical half-lives $T^f_{1/2}(0^+g.s.) = 6.8\cdot10^{18}$ y, $T^b_{1/2}(0^+g.s.) = 8.9\cdot10^{19}$ y for purely fermionic and bosonic neutrino and the NEMO-3 half-life limit $T_{1/2}(n=6) > 1.2\cdot10^{21}$ y we may evaluate the upper bound on bosonic fraction of the neutrino wave function :

$$\sin^2\chi < 0.27\ (90\%\ \text{C.L.})$$

The expected bosonic-to-fermionic decay branching ratio for the 2νββ transition to the ground state is small: r(0+ g.s.) = 0.076

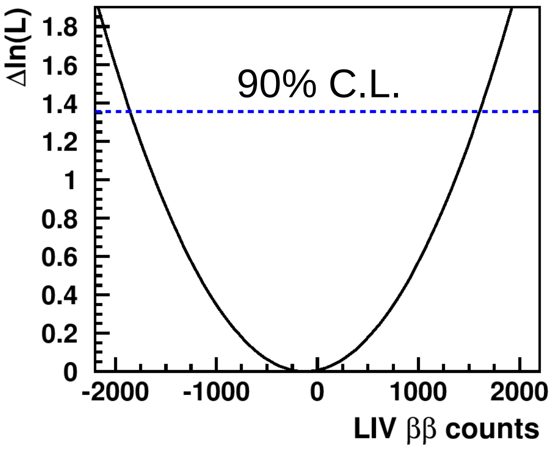
The situation is more promising for ^{100}Mo 2νββ decay to the 2^+_1 exited state, where this ratio is larger: $r(2^+_1) = 7.1$

Constraint on Lorentz invariance violation

The Lorentz invariance violation may be manifested as a perturbation in the 2νββ energy sum spectrum with a spectral shape n=4 with the amplitude defined by the value of parameter $\mathring{a}^{(3)}_{of}$, which is related to a time-like component of the LIV operator *J. S. Díaz, Phys. Rev. D 89, 036002 (2014)*.

The profile likelihood scan is used for limit setting to account for possibility of negative as well as positive perturbation. The NEMO-3 result for ^{100}Mo is:

$$-4.2 \times 10^{-7} \text{ GeV} < \mathring{a}^{(3)}_{of} < 3.5 \times 10^{-7} \text{ GeV (90\% C.L.)}$$



To be compared to the EXO-200 result for ^{136}Xe 2νββ decay *J. B. Albert et al., Phys. Rev. D 93, 072001 (2016)*:

$$-2.65 \times 10^{-5} \text{ GeV} < \mathring{a}^{(3)}_{of} < 7.6 \times 10^{-6} \text{ GeV (90\% C.L.)}$$

Possibility to determine the effective axial-vector coupling constant

A more accurate expression for the $2\nu\beta\beta$ decay rate is given in the paper
F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018) :

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\text{eff}}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{\left|\xi_{31}^{2\nu}\right|^2} \left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right) \qquad (39)$$

where the parameter, giving the ratio of nuclear matrix elements $\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$

may be determined from the measured $2\nu\beta\beta$-decay energy distributions, since the shapes of spectra for $G_0^{2\nu}$ and $G_2^{2\nu}$ are different.
This would provide a possibility to determine the quenching of g_A.

The parameter $\xi^{2\nu}_{31}$ may be evaluated with high statistics (5×10^5 events) low background (S/B ~80) ^{100}Mo $2\nu\beta\beta$ data of NEMO-3. Due to availability of the individual electron energy measurement in NEMO-3 the accuracy will be significantly better than in the case when only energy sum of two electrons is measured.

SUMMARY

- The results of investigation of $2\nu\beta\beta$ decay of ^{100}Mo with the full data set of the NEMO-3 experiment corresponding to a 34.3 kg·y exposure are reported.

- The summed energy of two electrons, the single electron energy and the angular distributions between the two electrons have been studied with statistics of 5×10^5 events.

- Analysis of the single electron energy demonstrates that HSD model is excluded with high confidence, while the SSD model is consistent with the NEMO-3 data.

- The ^{100}Mo $2\nu\beta\beta$ half life has been measured

$$T_{1/2} = [6.81 \pm 0.01\ (\text{stat}) +0.38-0.40\ (\text{syst})] \times 10^{18}\ \text{y}$$

- Limits on Majoron emitting neutrinoless double beta decay modes with spectral indices of n=2,3,7, as well as constraints on Lorentz invariance violation and on the bosonic neutrino contribution to the two-neutrino double beta decay mode are obtained.