EXPERIMENTAL TEST OF PAULI EXCLUSION PRINCIPLE

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OUTLINE

- Introduction
- Search for **anomalous carbon atoms**
- Search for transitions to **“non-Paulian”** states using detector **NEMO-2**
- Search for **“bosonic”** neutrino using **2β** decay data

I. INTRODUCTION

- The Exclusion Principle was formulated by **W. Pauli in 1925**

  (*even before the concept of spin was introduced!)*
- The **PEP** is valid for all identical particles with half-integral spin (fermions)
- The **PEP** forbids that two identical fermions occupy the same quantum state

THEORETICAL SITUATION

- **No satisfactory and consistent** mechanism of the **PEP** violation has been proposed so far
- **There is no** consistent theoretical framework within which the sensitivities of different experiments can be compared
- The exceptional place occupied by the **PEP** in modern physics does not imply that it does not need further painstaking experimental tests

EXPERIMENT

- Search for **non-Paulian** atoms and nuclei
- Search for transitions to **non-Paulian states** in atoms and nuclei
- Check the statistics of **neutrinos**

1. Search for anomalous atoms

- **"Non-Paulian"** atoms could be a cosmological origin, if not all **10^{80}** electrons in the universe are antisymmetrized or if spontaneous transitions of ordinary atoms into **"non-Paulian"** atoms are possible.
- The chemical properties of atoms with three electrons per **1s** shell must be similar to the properties of their "lower-order" neighbors in the periodic table (*for example, "non-Paulian" carbon is similar to boron*).

In 1989 Novikov and Pomansky proposed to search for anomalous atoms which arose in the universe during the nucleosynthesis. B-C and F-Ne were proposed as most promising candidates.

1) During the formation of the solar system, a differentiation of the original homogeneous protomatter occurred, according to the chemical properties of the elements. And finally, each element (Z) contains anomalous atoms of the element (Z+1). For example, boron will contain anomalous atoms of carbon.

$$\hat{C}/B = \hat{C}/C \times P(Z+1)/P(Z)$$

P(Z+1)/P(Z) = $2.18 \cdot 10^6$ for **B-C**
= **3300** for **F-Ne**

2) $C = t \cdot P(Z+1) / \tau \cdot P(Z)$

C is concentration of anomalous atoms in the host substance;
t is $\sim 4.5 \cdot 10^9$ **y** (average cosmological time interval during which anomalous atoms were in protomatter);
τ is the lifetime of an atomic electron with respect to violation of the **PEP;**
P(Z+1) and **P(Z)** are the cosmic abundance of elements.

Search for anomalous carbon atoms (JETP Lett. 68 (1998) 112)

- **P(C)/P(B) = 2.18·10⁶**

- **B: ^{10}B (19%) and ^{11}B (81%)**
- **C: ^{12}C (99%) and ^{13}C (1%)**

The anomalous atom **$^{12}\hat{C}$** contains **three *K*-shell** electrons and behaves chemically like a boron atom

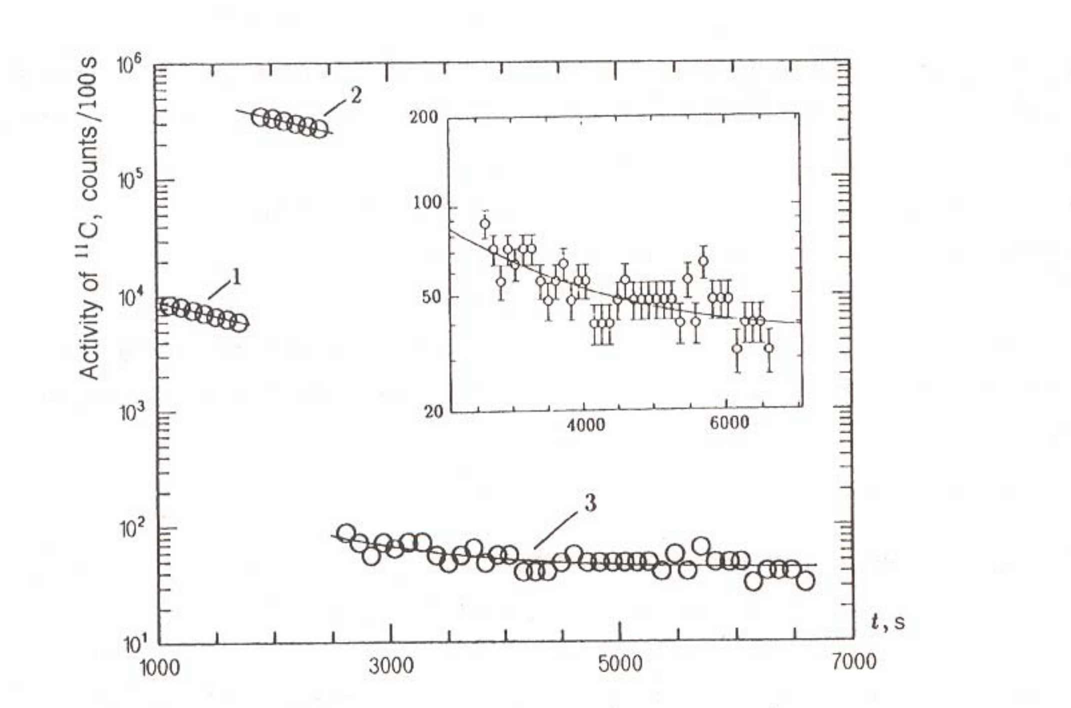
The idea of the experiment is to remove <u>carbon atoms</u> chemically from a boron sample and then to measure the content of <u>carbon nuclei</u> in it.

- The search for **Ĉ** was conducted by **γ-activation** analysis (this method does not produce any radioactive isotopes in B)
  $^{12}C(\gamma,n)^{11}C$; $^{11}C(20.38\ m) \rightarrow {}^{11}B + \beta^{+} + \nu$
- The experiment was performed on the microtron at the **Institute of Physics Problems of the Russian Academy of Science**
- Boron grown by zone melting was used (initial content of carbon is $\mathbf{1.5 \cdot 10^{-3}\ g/g}$)

Procedure

- A boron sample **(~ 0.1 g**) was irradiated with **γ-ray** bramsstrahlung from 28 MeV electrons
- After irradiation the boron sample was purified <u>chemically</u> from carbon
- Activity of **^{11}C <u>nuclei</u>** remaining in the boric acid solution was measured as a function of time (using **γ-γ coincidence** method)

^{11}C activity versus time



1 - carbon separated from 0.1 g of boron after irradiation

2 - 0.006 g of carbon after irradiation (for comparison)

3 – boron (after chemical separation of carbon)

Inset: the detected positron activity in the boron solution.

There is a “positive” effect!!!

(Of course, it can be connected with rest of normal carbon in the boron sample.)

RESULTS

- Concentration of anomalous carbon atoms in boron is **$\leq 5\cdot10^{-6}$ g/g**

  ⇓

- Concentration of anomalous carbon atoms in carbon is **$^{12}\hat{C}/^{12}C \leq 2.5\cdot10^{-12}$**

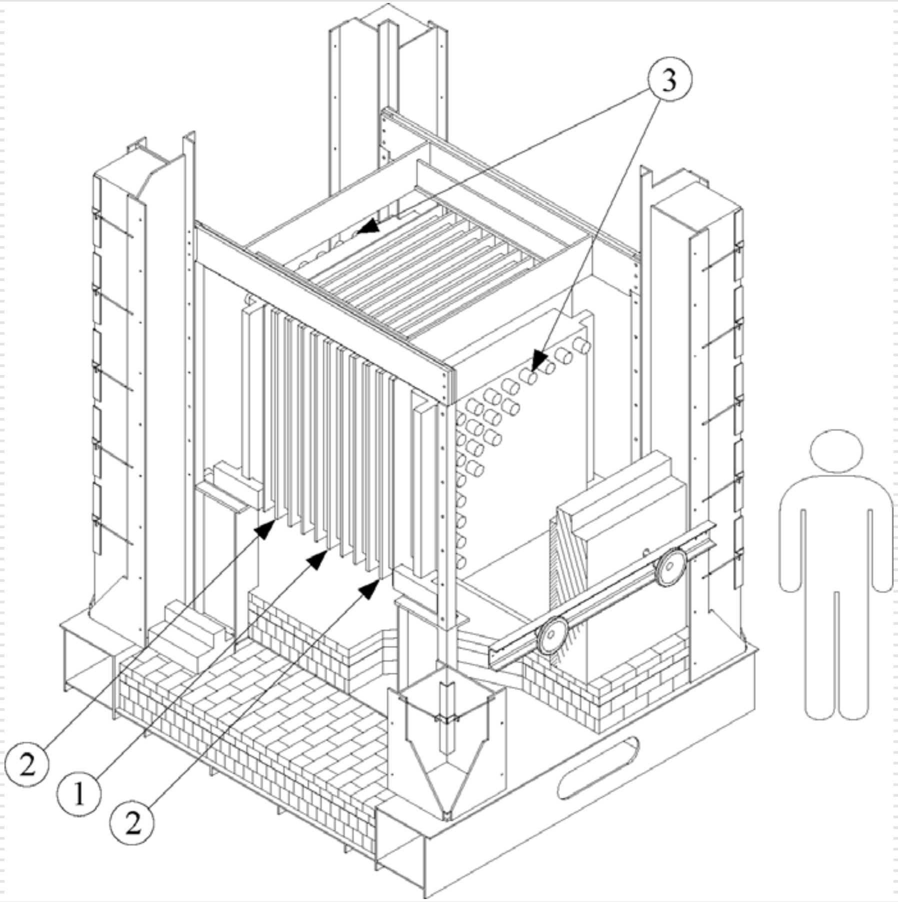
  ⇓

- The lifetime of electrons in a carbon atom relative to violation of the PEP **$\tau \geq 2\cdot10^{21}$ y**

Best present limits

Be'/Be	$< 9\cdot10^{-12}$	Phys. Rev. Lett 85 (2000) 2701
$^{12}\hat{C}/^{12}C$	**$\leq 2.5\cdot10^{-12}$**	**JETP Lett. 68 (1998) 112**
$^{20}\tilde{N}e/^{20}Ne$	$< 2\cdot10^{-21}$	Phys. Lett. B 240 (1990) 227
$^{36}\tilde{A}r/^{36}Ar$	$< 4\cdot10^{-17}$	Phys. Lett. B 240 (1990) 227

2. Search for **“non-Paulian”** transitions using detector **NEMO-2**



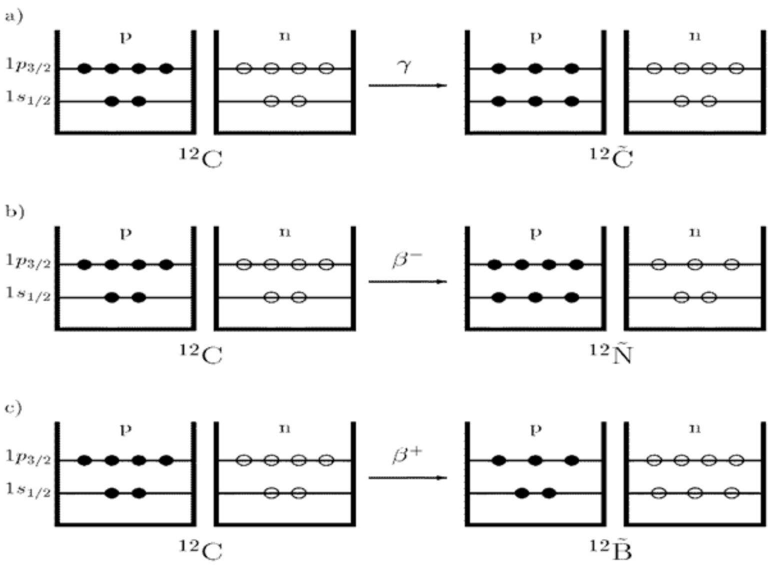
1 – Central frame with the source plane

2 – tracking device

3 – two scintillator walls

Full mass of ^{12}C is 170 kg

Non-Paulian transitions



Non-Paulian process with high energy **γ-quantum** emission ($E\gamma \approx 18$ MeV)

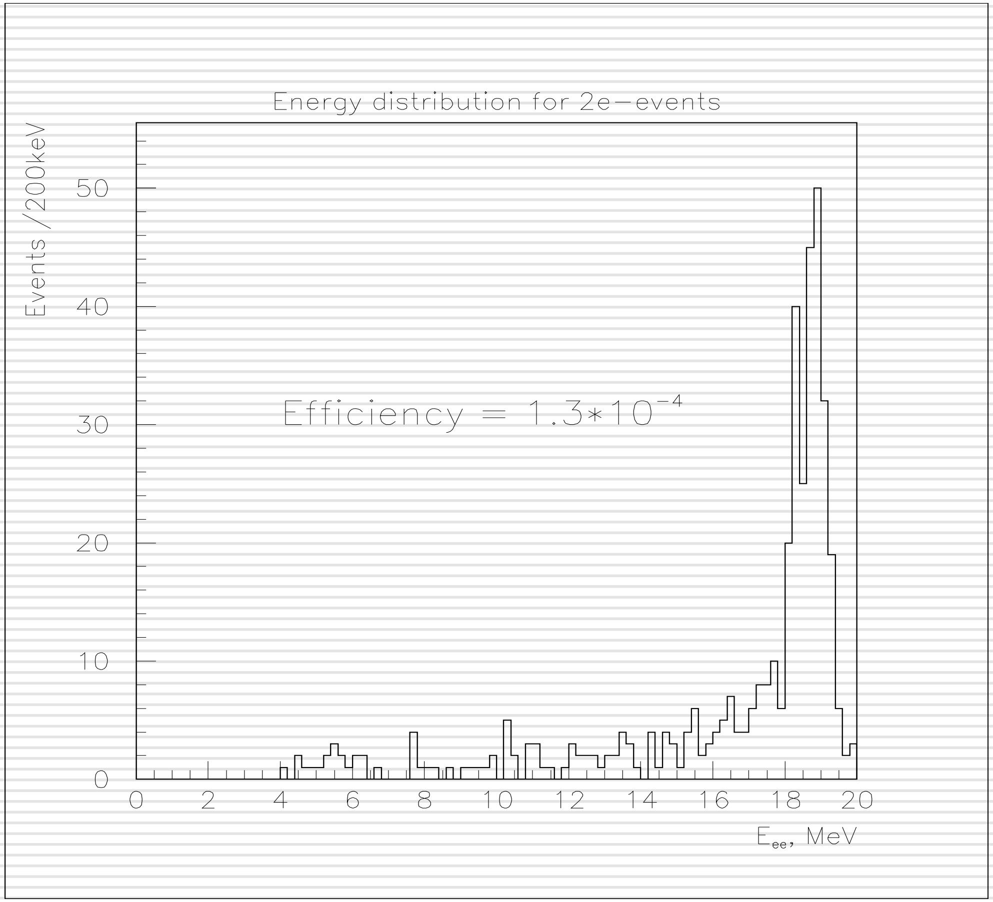
Non-Paulian **β^- decay**

($Q_\beta \approx 19$ MeV)

Non-Paulian **β^+ decay**

($Q_\beta \approx 17$ MeV)

Non-Paulian process with high energy γ-quantum emission



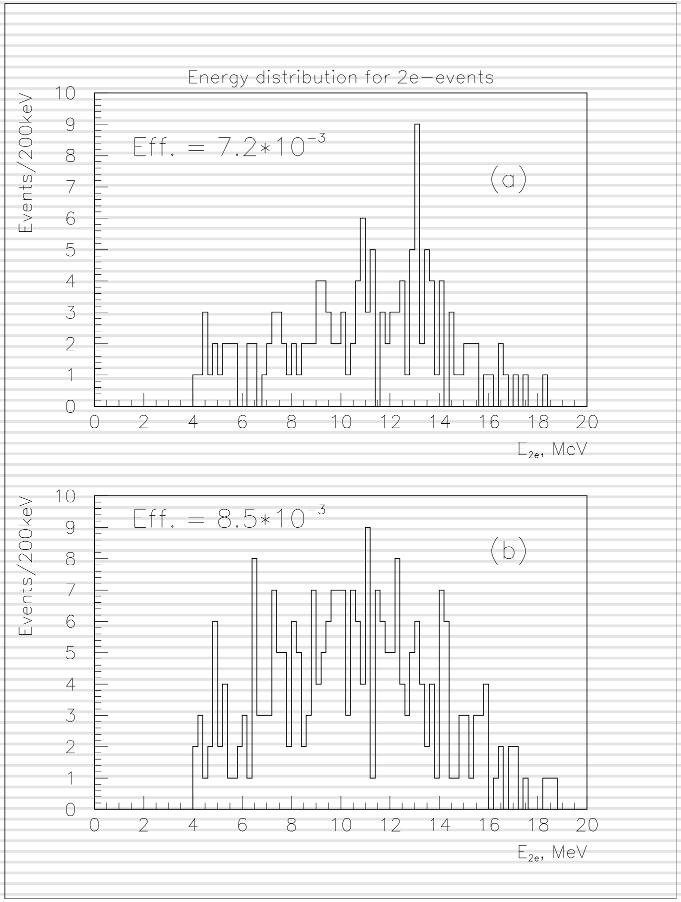
We are looking for **e^+e^-** pair created in the source.

Efficiency was calculated by MC.

No events with two tracks and summed energy **>4 MeV** were found after **16945 h** of measurements

$T_{1/2}$ > $4.2 \cdot 10^{24}$ y at 90% C.L.

$\beta^{\pm}$ decays to non-Paulian states



β^{+}

β^{-}

We are looking for **two tracks events.**

<u>Selection:</u> electron appears in a plastic scintillator, cross the tracking volume and source and enter a plastic scintillator on the opposite side of the detector.

Efficiency was calculated by MC

One event with energy **> 4 MeV** was found (2163 h with antineutron shield)

$T_{1/2}(\beta^{+}) > 2.6 \cdot 10^{24}$ y and $T_{1/2}(\beta^{-}) > 3.1 \cdot 10^{24}$ y at 90% C.L.

RESULTS (Eur. Phys. J. A 6 (1999) 361)

Channel	γ emission	β^-	β^+
Energy window (MeV)	[4,20]	[4,20]	[4,20]
Number of events	0	1	1
Efficiency	$1.3 \cdot 10^{-4}$	$8.5 \cdot 10^{-3}$	$7.2 \cdot 10^{-3}$
$T_{1/2}$, y (90% CL)	**$> 4.2 \cdot 10^{24}$**	**$> 3.1 \cdot 10^{24}$**	**$> 2.6 \cdot 10^{24}$**
Best previous results	$> 1.3 \cdot 10^{20}$ [1]	$> 8 \cdot 10^{27}$ [2]	$> 8 \cdot 10^{27}$ [2]

[1] B.A. Logan and A. Ljubicic, PR C20 (1979) 1957.

[2] D. Kekez, A. Ljubicic, B.A. Logan, Nature 348 (1990) 224.

Borexino CTF in 2004: **> $2.1 \cdot 10^{27}$ y** ($^{12}C \rightarrow {}^{12}\hat{C} + \gamma$)

- Sensitivity of **NEMO-3**:
  ~ 10^{27} y
- Sensitivity of **SuperNEMO**:
  ~ 10^{28} y

3. Search for **“bosonic”** neutrino using **2β** decay data

- In 2005 **Dolgov and Smirnov** assumed that the **PEP** is violated for neutrinos and, consequently, neutrinos obey (at least partly) the Bose-Einstein statistics [PL B 621 (2005) 1]
- **Consequences of this assumption:**

a) neutrinos may form cosmological Bose condensate (**dark matter!)**

b) “wrong” statistic of neutrinos could modify Big Bang nucleosynthesis

c) spectra of the supernova neutrinos may be changed

d) **PEP** violation for neutrinos can be tested in the two neutrino **double beta decay** experiments

Why it can be possible for neutrinos?

- **PEP never was checked for neutrinos**
- Neutrinos are only known neutral leptons
- Neutrino can be a Majorana particle ($\nu \equiv \nu'$) and violate lepton number conservation
- Neutrino has a very small mass

If neutrino is bosonic (or partially bosonic) particle one can see the effect in 2β(2ν) decay:

- Probability of decay will be changed
- Sum and single electron energy spectra will be changed
- Angular distribution will be changed

So, 2β(2ν) decay is nice process to check possible PEP violation in neutrino sector

A.S. Barabash, A.D. Dolgov, R. Dvornicky, F. Simkovic, A.Yu. Smirnov, Nucl. Phys. B 783 (2007) 90.

- The amplitude of the **$2\beta(2\nu)$** decay can be parametrized as

$$A_{2\beta} = \cos^2\chi A_f + \sin^2\chi A_b$$

- The probability of **$2\beta(2\nu)$** decay is equal to:

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

where $W_{f,b} \sim |A_{f,b}|^2$

Predictions for decay rate:

- ^{100}**Mo:**

Theory: $T_{1/2}^{f}(0^{+}_{g.s.}) = (6.8 \pm 3.4)) \cdot 10^{18}$ y, $T_{1/2}^{b}(0^{+}_{g.s.}) = 8.9 \cdot 10^{19}$ y

Experiment: $T_{1/2}(0^{+}_{g.s.}) = (7.1 \pm 0.4) \cdot 10^{18}$ y,

- ^{76}**Ge:**

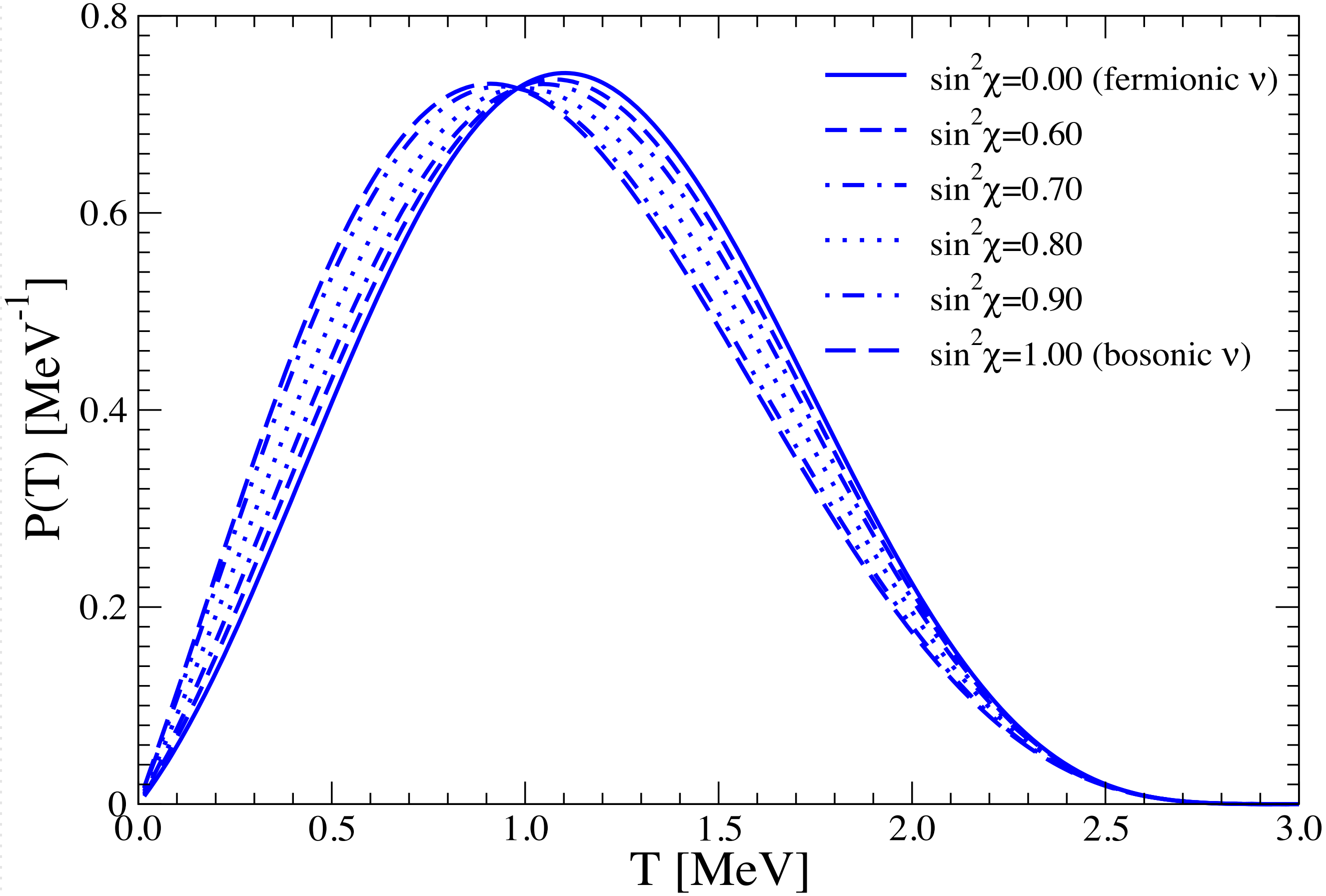
Theory: $T_{1/2}^{f}(0^{+}_{g.s.}) = (0.8\text{-}1.4) \cdot 10^{21}$ y, $T_{1/2}^{b}(0^{+}_{g.s.}) = 1.5 \cdot 10^{24}$ y

Experiment: $T_{1/2}(0^{+}_{g.s.}) = (1.5 \pm 0.1) \cdot 10^{21}$ y,

Conclusion: $\sin^2\chi < 0.5$

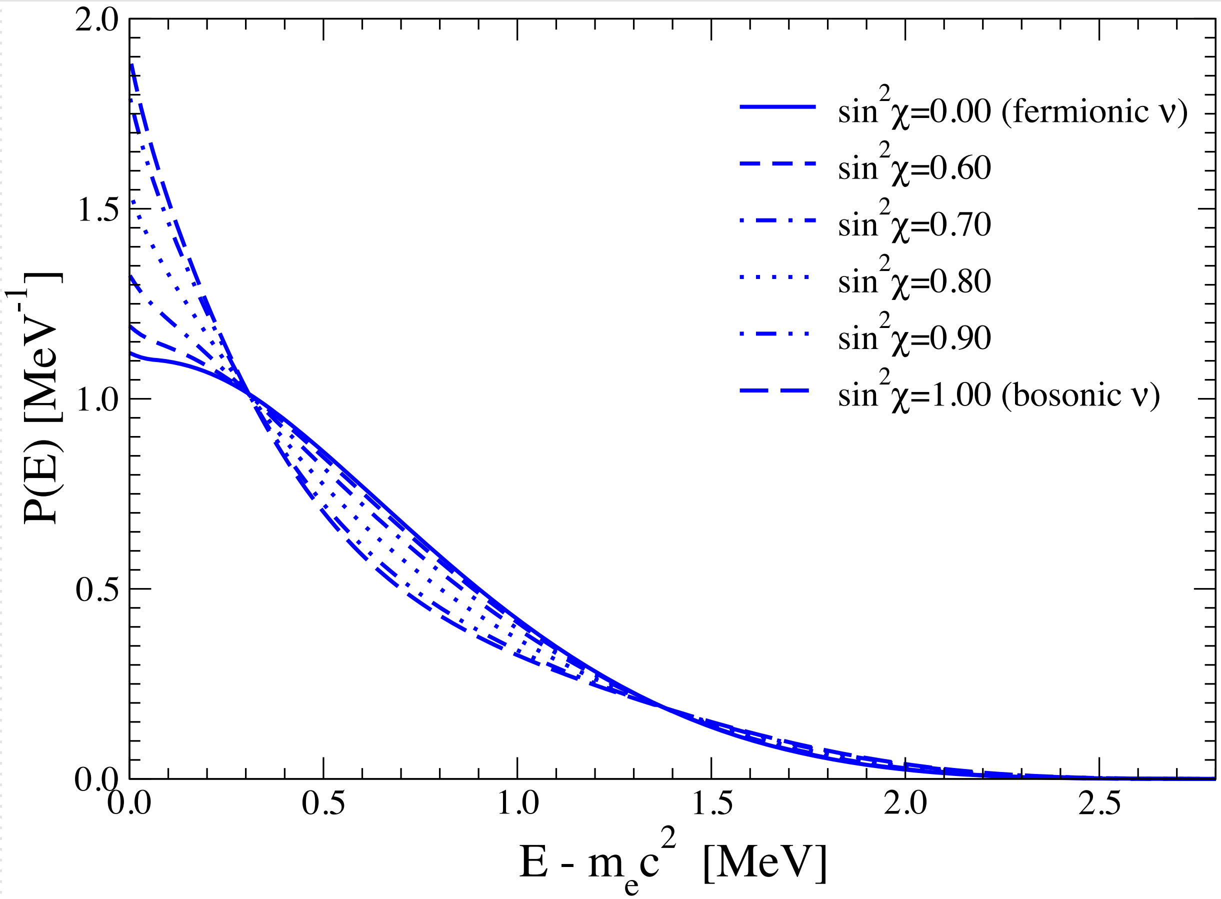
The normalized distribution of the total energy of two electrons

$^{100}Mo(0^+_{g.s.}) \to {}^{100}Ru(0^+_{g.s.})$



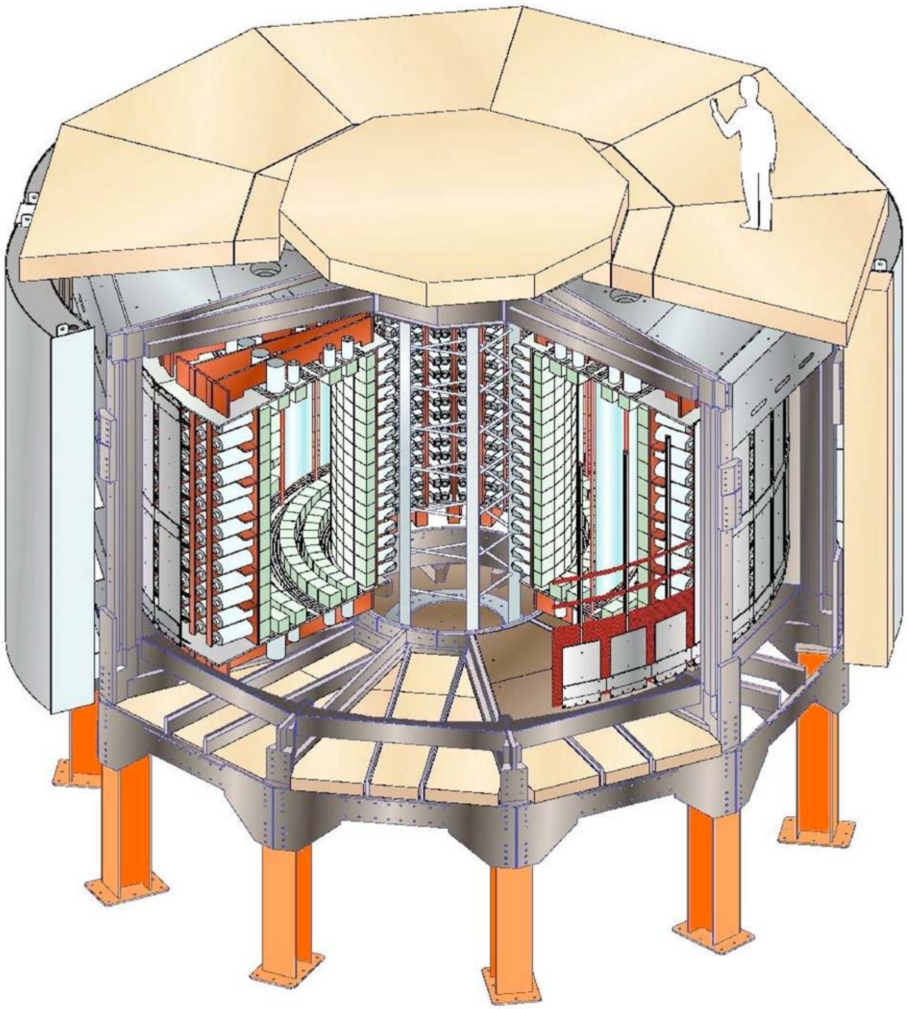
The normalized distribution of the single electron energy

$^{100}Mo(0^+_{g.s.}) \rightarrow {}^{100}Ru(0^+_{g.s.})$



The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 60 mg/cm²

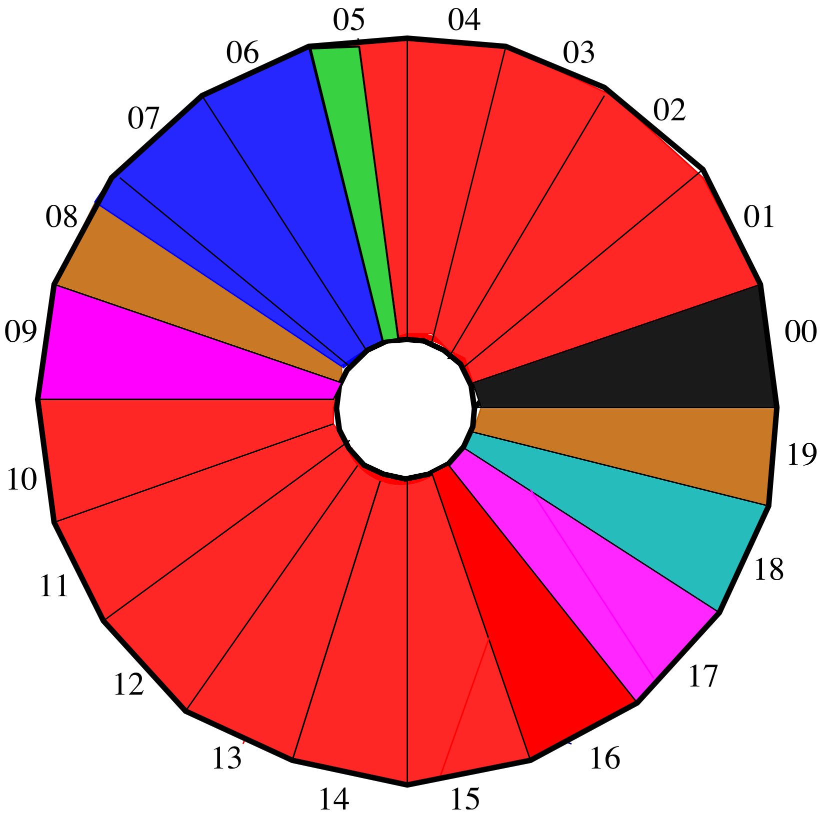
Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

Able to identify e^-, e^+, γ and α

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

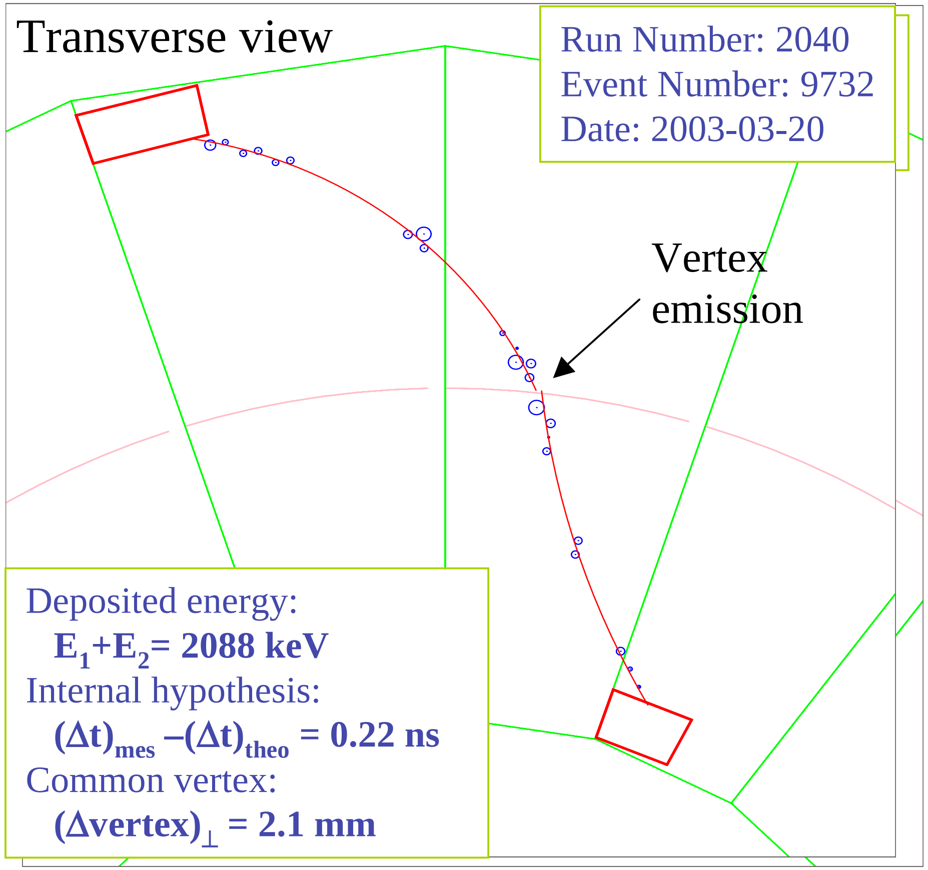
Cu 621 g

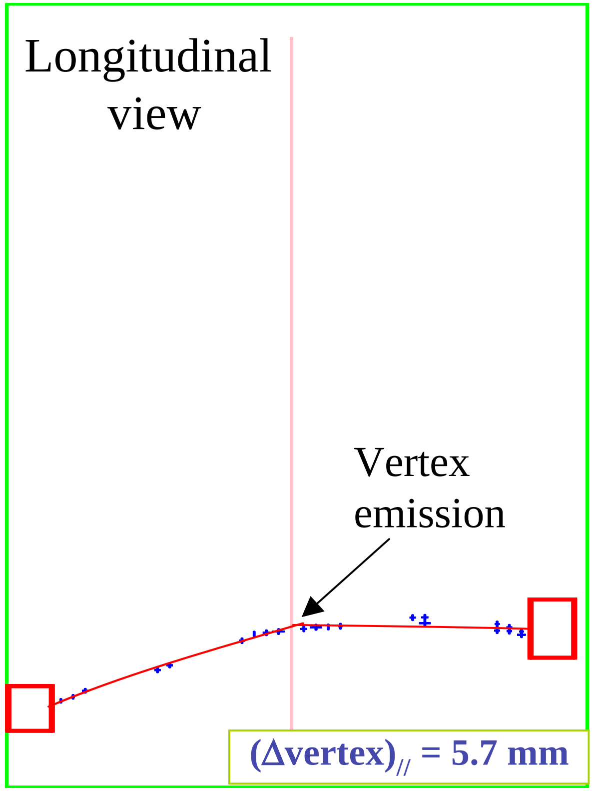
External bkg measurement

(All enriched isotopes produced in Russia)

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





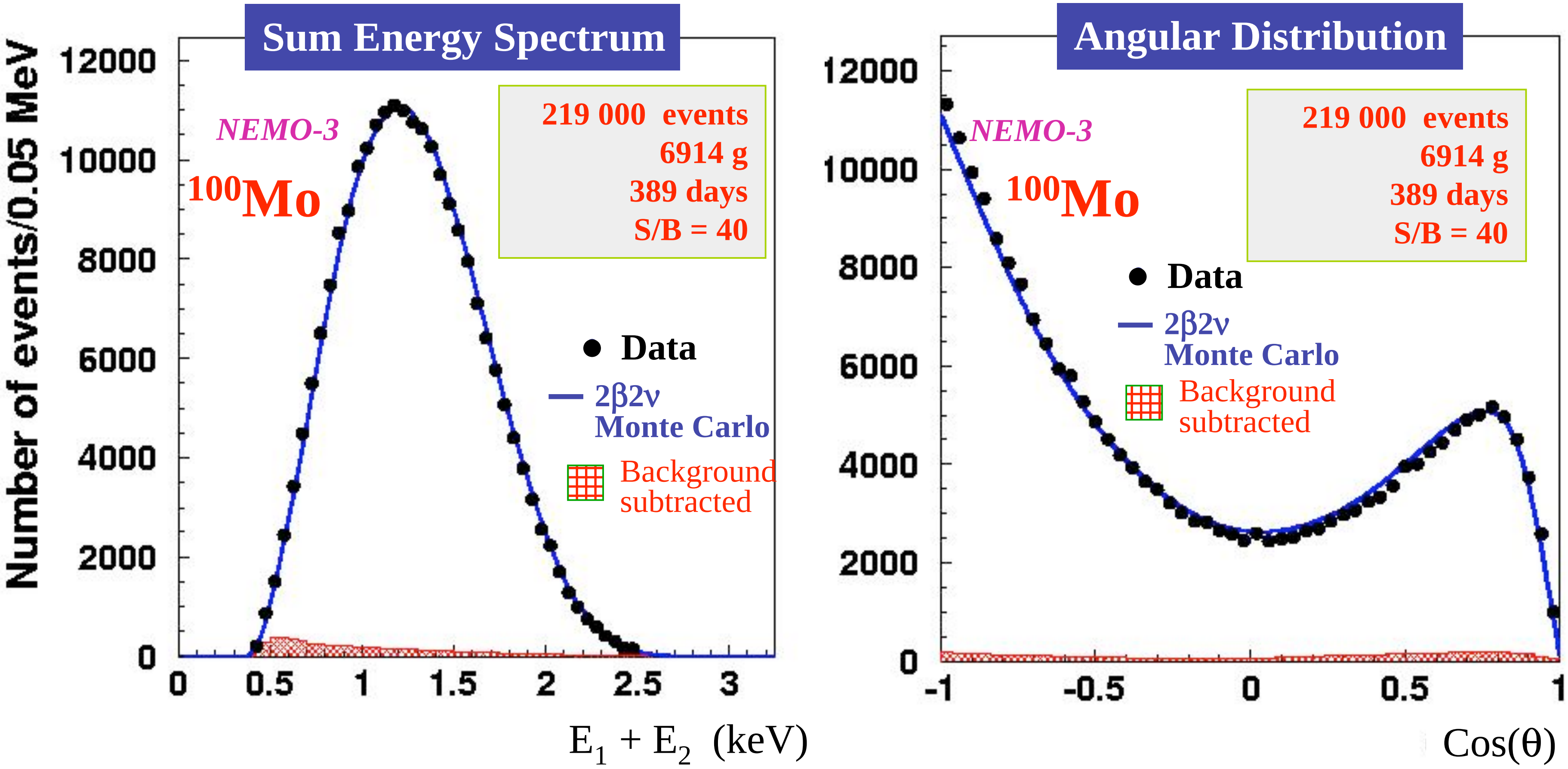
Trigger: at least 1 PMT > 150 keV

≥ 3 Geiger hits (2 neighbour layers + 1)

Trigger rate = 7 Hz

^{100}Mo 2β2ν result

(Phase I: Feb. 2003 – Dec. 2004)



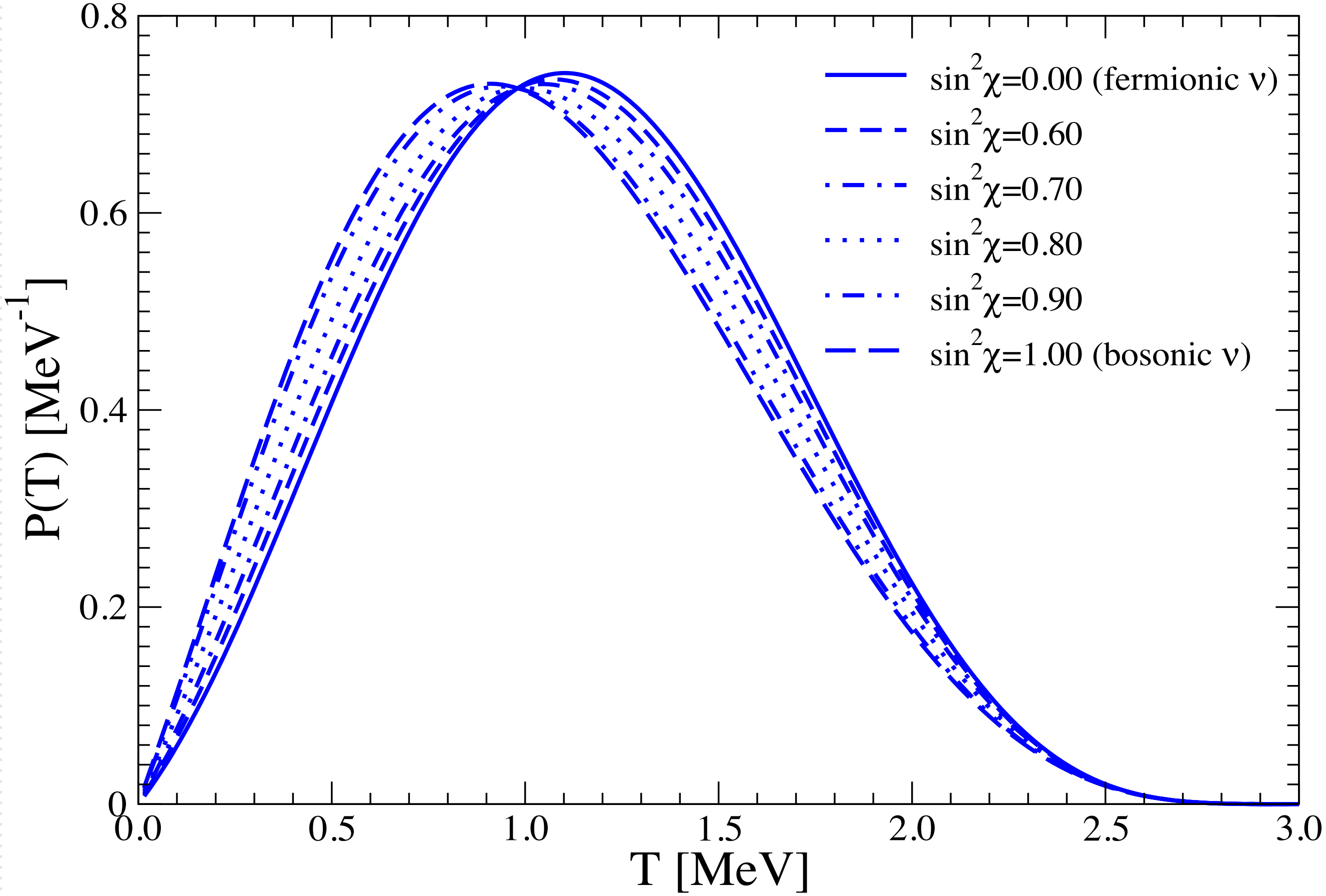
7.37 kg.y

$T_{1/2} = 7.11 \pm 0.02$ (stat) ± 0.54 (syst) $\times 10^{18}$ y

Phys. Rev. Lett. 95 (2005) 182302

The normalized distribution of the total energy of two electrons

$^{100}Mo(0^+_{g.s.}) \to {}^{100}Ru(0^+_{g.s.})$



Large admixture of bosonic ν is excluded: $\sin^2\chi < 0.6$

Conservative limit is $\sin^2\chi < 0.6$
(In fact, best fit gives $\sin^2\chi \approx 0.4$-0.5)

- This is because of the existing disagreement between the data and Monte Carlo simulations (of course, it can be just systematic effect).
- **NEMO-3** is current experiment. Systematic will be reduced and sensitivity to ***bosonic neutrino*** will be improved down to **$\sin^2\chi \approx$ 0.2** (**or bosonic nature of neutrino will be established!**).

^{100}Mo. Decay to 2^+ excited state

- $T_{1/2}(2^+_1)$ = $1.7\cdot10^{23}$ y (**fermionic ν**)
  = $2.4\cdot10^{22}$ y (**bosonic ν**)

$r_0(2^+_1) = 7.1$

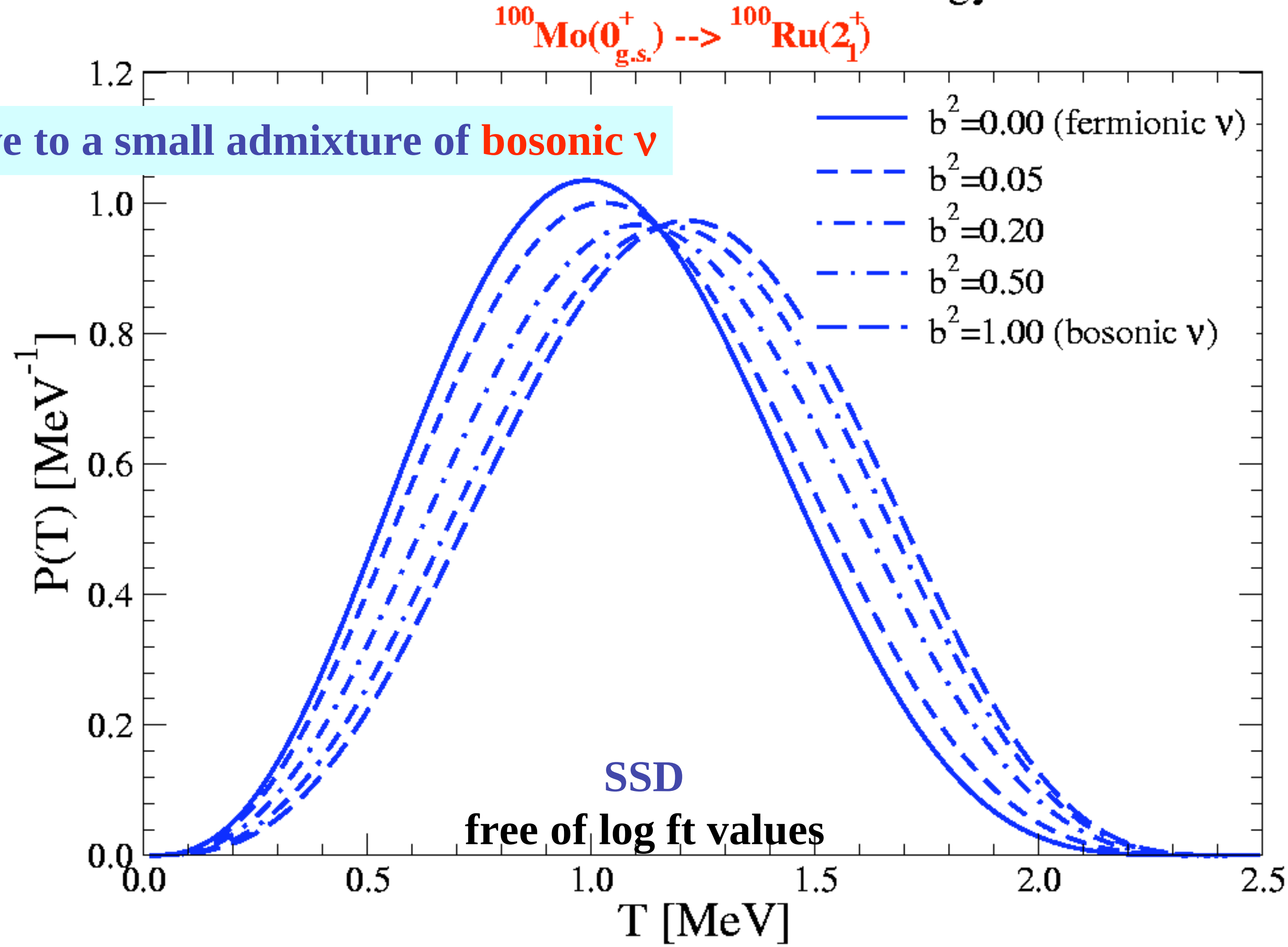
Best present limit is **> $1.6\cdot10^{21}$ y**

Final sensitivity of **NEMO-3** is **~ 10^{22} y**

Sensitivity of **SuperNEMO** is **~ 10^{23} y**

The normalized distributions of the total energy of two electrons

Sensitive to a small admixture of bosonic ν



SSD

free of log ft values

HSD nuclei even more sensitive to admixture of bosonic ν
but calculation of M.E. needed

CONCLUSION

- A search for anomalous carbon atoms $^{12}\hat{C}$, atoms with three *K*-shell electrons, is done . A limit on the existence of such atoms was determined: $^{12}\hat{C}/^{12}C \leq 2.5 \cdot 10^{-12}$.
- It corresponds to a limit on the lifetime with respect to violation of **PEP** by electrons in carbon atom of $\tau \geq 2 \cdot 10^{21}$ y.

CONCLUSION (continuation)

- The **PEP** was tested with the **NEMO-2** detector:

$T_{1/2}$ **> 4.2·10²⁴ y ($^{12}C \to {}^{12}\hat{C} + \gamma$)**

> 3.1·10²⁴ y ($^{12}C \to {}^{12}\tilde{N} + e^- + \nu$)

> 2.6·10²⁴ y ($^{12}C \to {}^{12}B' + e^+ + \nu$)

- Using **NEMO-3** and **SuperNEMO** detectors sensitivity could be increased to **~ 10^{27}-10^{28} y**

CONCLUSION (continuation)

- First time **PEP** was checked for neutrino
- **Pure bosonic** neutrinos are excluded by the present **2β** decay data
- The existing **2β** decay data allow to put the conservative upper bound

  $\sin^2\chi < 0.6$
- Sensitivity could be increased up to ~ **0.05-0.1** for $\sin^2\chi$ (or we will see the "positive" effect)