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Double beta decay (experiment)

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The popular review of the double beta decay investigation is presented. The past, present and future experiments are discussed from the point of the view their sensitivity to Majorana neutrino mass.

Key words: neutrinoless double beta decay, Majorana neutrino, Time Projection Chamber

Fig. - 28.

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1.1 Introduction.

The particular role of the double beta decay investigations among the many approaches to study the neutrino properties is connected with the fact that it can provide an unique and very sensitive probe of a new physics beyond the Standard Model such as nonzero Majorana neutrino mass, right-handed admixture in weak interaction, violation of the lepton conservation law, the dark matter existence, and other topics.

Double beta decay is extremely rare second order weak process, which simultaneously converts two neutrons in atomic nucleus into two protons. Generally there are three modes of this decay, which are discussed.

First is two neutrino double beta decay and proceeds with emitting two beta particles and two anti-neutrinos. This decay mode is predicted by the standard theory of the weak interactions.

$$(A, Z) \rightarrow (A, Z+2) + 2\beta^- + 2\nu_e$$

Description of the other two commonly discussed decay modes requires extensions to the Standard Model. Neutrinoless decay occurs when antineutrino from one β -decay is absorbed as a neutrino in the second β -decay, producing only two beta particles.

$$(A, Z) \rightarrow (A, Z+2) + 2\beta^-$$

Re-absorption of the neutrino requires, that the neutrino be massive Majorana particle (antiparticle is equal to particle) and the absence of antineutrino in the final state means that this mode violates lepton number conservation.

Zero-neutrinos decay, accompanied by emission of a majoron, also lacks antineutrinos in the final state and requires, that beta decay neutrinos couple to Goldstone boson, associated with breaking of the (B-L) symmetry.

$$(A, Z) \rightarrow (A, Z+2) + 2\beta^- + \chi$$

Feynman diagrams for each of these modes in two nucleons mechanism are presented at Fig. 1.

Modern experiments use the energies of the emitted electrons as their primary tool for detecting 2β -decay. Fig.2 shows the expected sum-energy distributions of the different decay modes. All modes have relatively distinctive signatures, especially neutrinoless mode, it is a delta function at the transition energy.

The $2\beta 2\nu$ -decay rate can be written this way

$$W^{2\nu} \sim [T_{1/2}^{2\nu}]^{-1} = F^{2\nu} * |M^{2\nu}|^2$$

and depends only on two parameters: easily calculated phase space integral and nuclear matrix element for the transition. Matrix element must be calculated using complicated nuclear theory. And although 2ν -mode isn't interesting on its own, a comparison of two neutrino half-life measurement with predicted one provides a good check of nuclear matrix calculation technique. This check is important, because the decay rates of the other modes depend on the similar parameters plus extra parameters, which are the quantity of the interest to the particle physicists.

Neutrinoless decay rate depends on the neutrino mass.

$$W^{0\nu} \sim [T_{1/2}^{0\nu}]^{-1} = F^{0\nu} * |M^{0\nu}|^2 * \langle m_\nu \rangle^2$$

Similarly for neutrinoless decay with majoron emitting, the decay rate depends from $\langle g_{\nu\chi} \rangle$ -the neutrino- majoron coupling constant.

$$W^{0\nu\chi} \sim [T_{1/2}^{0\nu\chi}]^{-1} = F^{0\nu\chi} * |M^{0\nu\chi}|^2 * \langle g_{\nu\chi} \rangle^2.$$

1.2 Historical overview.

Double beta decay searches have a long and very interesting history.

In 1935 M.Goeppert-Meyer first calculated the probability for the 2β -decay, using the new Fermi theory of weak decays and predicted half-life time in excess of 10^{20} years.

Majorana (1937) proposed, that the antiparticle might be indistinguishable from the particle, and then Racah (1937) suggested an experimental test for detecting Majorana neutrino, neutrinoless 2β -decay. Antineutrino from one beta decay might be absorbed by the second neutron (not necessary in the same nucleus).

Furry (1939) realised that $2\beta 0\nu$ -decay could be mediated by virtual neutrino and predicted the half-life on the level $T_{1/2} \sim (10^{12} - 10^{15})$ years.

First experiment ^{124}Sn , made by Fireman in 1949, claimed that 2β -decay of ^{124}Sn had been observed with half-life $T_{1/2} \sim (4-9) \cdot 10^{15}$ years. Subsequent experiments failed to reproduce positive result and there were obtained $T_{1/2} > 10^{17}$ years.

The discovery by Wu (1957) parity violation in weak interaction [Wu57] reopened Dirac-Majorana question, since the long $2\beta 0\nu$ -decay half-life limits could be explained by parity alone, an virtual antineutrino had a wrong helicity to be absorbed as a neutrino. Modern theories allow for the helicity reversal of Majorana neutrinos due to non-zero neutrino mass or for contribution from right-handed weak processes.

The first hints of the 2β -decay discovery were obtained in the work [Ing50], through the analysis of isotopic abundance's of the 2β -decay parent and daughter atoms in the ancient ore samples. $T_{1/2}(^{130}\text{Te}) = 1.4 \cdot 10^{21}$ years was obtained. This result was in poor agreement with the predictions. But later geochemical experiments confirmed first result for 2β -decay rate of ^{130}Te isotope [Kir68].

Between 1950-1988 there were made many experiments used different techniques such, as cloud chamber, scintillation counters, spark chamber, Ge(Li)-detectors, photographic emulsions. The detailed list of the all experiments can be found in review [Hax84], also as the references on the theoretical calculations.

First direct laboratory observations of 2β -decay were made by two groups: ITEP-YePI group observed $2\beta 2\nu$ -decay of ^{76}Ge with the time $T_{1/2}(^{76}\text{Ge}) = 1 \cdot 10^{21}$ years [Vas90], first publication was in 87, Irvine group obtained $2\beta 2\nu$ half-life for ^{82}Se : $T_{1/2}(^{82}\text{Se}) = 1 \cdot 10^{20}$ years [Ell87].

There were made many theoretical works , which tended to agree with experimental results, for example [Sta90].

Double beta decay investigation is even more popular now than 20 years ago. About 40 experiments are underway, using more than dozen different techniques.

2.1 Possible candidates for double beta decay.

Double beta decay occurs only for even-even atoms. One can see it easily on the Fig.3, where the dependence of the atom mass from Z (the charge of nucleus) are presented, separately for even A and odd A (atomic mass). Beta decay can proceed from $Z=52$ towards the lower energy states until nucleus becomes ^{136}Xe (xenon). At this point beta decay to ^{136}Cs (cesium) is energetically forbidden. It is possible , however, for ^{136}Xe to decay directly to ^{136}Ba (barium) by undergoing two simultaneous beta decays, tunnelling through the forbidden intermediate state. The similarly, $2\beta^+$ -decay is possible from ^{136}Ce to ^{136}Ba . For odd A we can see the flat dependence.

There are 35 pair atoms for which are possible $2\beta^-$ -decay , and 34 pair atoms , possible for $2\beta^+$ -decay. In the case of $2\beta^+$ -decay its are possible two other modes: the electron capture and β^+ -decay, and the double electron capture.

2.2 Energy dependence of decay rates.

The energy, realised in these decays, are different :

$$\begin{aligned} Q &= \Delta M && \text{for } 2\beta^- \text{-decay} \\ Q &= \Delta M - 4m_e && \text{for } 2\beta^+ \text{-decay} \\ Q &= \Delta M - 2m_e - E_{\text{kin}} && \text{for } \varepsilon \text{-capture and } \beta^+ \text{-decay} \\ Q &= \Delta M - 2E_{\text{kin}} && \text{for } 2\varepsilon \text{-capture,} \end{aligned}$$

where ΔM is the mass difference between the parent and daughter atoms, E_{kin} is binding energy of the electrons.

On the Fig.4 there are presented the mass differences between the parent and daughter isotopes for $2\beta^-$ and $2\beta^+$ - nuclides. Maximal energy realised in the double beta transition is equal to 4.27 MeV for ^{48}Ca , the second good isotope is ^{150}Nd with decay energy 3.37 MeV. The famous isotope ^{76}Ge has transition energy 2.04 MeV. And only 11 isotopes have the energy more

than 2 MeV. For $2\beta^+$ -nuclides these transition energies are smaller, because it must be decrease on 2 MeV ($4m_e$).

Fig.5 are presented the abundance for the same isotopes. As rule, all interesting isotopes have the abundance in the natural composition less than 10%. We have for ^{48}Ca only 0.3%, for ^{150}Nd 5.6%, for ^{76}Ge 7.8%. And only two Te isotopes have large abundance, more than 30%. The abundance for $2\beta^+$ -nuclides are smaller.

The rates of all decay modes, commonly discussed, have the different dependence from the transition energy [Sch84]. Double neutrino decay rates is proportional to energy in 11.

$$W_{2\nu} \sim Q^7 \{Q^4 + 22Q^3 + 220Q^2 + 990Q + 1980\},$$

where $Q = \Delta M/m_e$ is decay energy, expressed in mass of the electron.

Neutrinoless decay rate with mass mechanism has dependence as energy in 5.

$$W_{0\nu}^{<m>} \sim Q^4 \{Q^4 + 10Q^3 + 40Q^2 + 60Q + 30\},$$

Neutrinoless decay rate with right handed current mechanism and decay rate with an emitting of the Majoron are proportional to the energy in 7.

$$W_{0\nu}^{<RHC>} \sim <Q>^7, \quad W_{0\nu\chi} \sim <Q>^7.$$

Coulomb function can be applied to each electron (or positron), here is presented this function in nonrelativistic approximation.

$$F_{\pm}(Z, E) \approx 2\pi\alpha Z/c (E/p) [1 - \exp(\pm 2\pi\alpha Z/c)]^{-1}.$$

Only the few isotopes with $Q > 2$ MeV generally study experimentally, due to the extremely strong dependence of decay rates from the transition energy.

3.1 Limits on parameters governing new physics.

The observation of neutrinoless double beta decay would imply the existence of the processes beyond the Standard Model. Up to now the neutrinoless double decay didn't observed, so only the associated half-life limit could be established. The general expression for the $(0^+ \rightarrow 0^+)$ $2\beta 0\nu$ -decay rate is of the form

$$[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = C_1 (<m_{\nu}>/m_e)^2 + C_2 <\lambda> <m_{\nu}>/m_e \cos\psi_1 + \\ + C_3 <\eta> <m_{\nu}>/m_e \cos\psi_2 + C_4 <\lambda>^2 + C_5 <\eta>^2$$

where the C_i contains both matrix elements and phase-space integrals, for example,

$$C_1 = G^{0\nu} |M_{GT}^{0\nu} - g_v^2/g_a^2 M_F^{0\nu}|^2.$$

Definitions of the other C_i are more complicated, and may be found in [Doi85]. The Ψ_i are phase angles between $\langle m_\nu \rangle$ and the complex parameters $\langle \lambda \rangle$ and $\langle \eta \rangle$. If CP is conserved, these angles are taken as either 0 or π . The parameters in equations are effective values of the neutrino mass and RHC coupling strength, defined by

$$\langle m_\nu \rangle = \sum_j \epsilon_j m_j U_{ej}^2, \quad \langle \lambda \rangle = \lambda \sum_j \epsilon_j U_{ej} V_{ej}, \quad \langle \eta \rangle = \eta \sum_j \epsilon_j U_{ej} V_{ej}$$

where m_j are the neutrino eigen-masses, U_{ij} and V_{ij} are mixing matrices, λ and η are dimensionless coupling constants for RHC weak interactions, and ϵ_j are the CP parities of the neutrinos. The presence of the ϵ_j in definition of $\langle m_\nu \rangle$ allows for the possibility of mass term cancellations, which would reduce the magnitude of a $2\beta 0\nu$ -decay signal.

Trustworthy restriction for the neutrino mass and other parameters from measured half-life limits are possible only in the case of a reliable calculations of the nuclear matrix elements.

Since 0ν -decay hasn't been observed, only way is to use the positive $2\beta 2\nu$ -decay to test the assumption made in the nuclear structure calculations.

I don't want to discuss further the decay with Majoron emitting. Simple triplet majoron model, proposed by Gelmini and Ronsadeli [Gel81], was ruled out by LEP results on Z^0 width. More sophisticated models with emitting of two, three or more majorons were proposed, but these models practically ruled out now experimentally [Kla96].

I shall interpret the zero neutrinos results only from the point of view neutrino mass, because there is a well-known argument [Sch82] to illustrate the $2\beta 0\nu$ implies a Majorana neutrino mass. First diagram ($2\beta 0\nu$ -decay) on Fig.6(a) can always be closed in gauge theory to provide a diagram Fig.6(b), which means the mass member. Thus whatever mechanism be responsible for $2\beta 0\nu$, a neutrino Majorana mass is unavoidable.

The neutrino mass information provided by $2\beta 0\nu$ -decay (through the existence or absence of this process) is complementary to that, obtained from solar neutrinos, neutrino oscillations or β -spectrum endpoint energy measurements (see Fig.7). It refers, however, to self-conjugated Majorana neutrino.

3.2 Matrix element calculations.

Three main approaches have been used most intensively to calculate the nuclear matrix elements: the nuclear shell model, the quasiparticle random phase approximation (QRPA) and the operator expansion method (OEM). Full computation in the shell model [Doi81, Hax84] were

unattainable, because the number of basic states in model space increased explosively for nuclei heavier than ^{48}Ca and various simplifications had to be introduced, "the closure approximation" for example. Results of such calculations were not in good agreement with experiment.

QRPA model [Vog86, Sta90, Tom91] is more attractive so far, as the new vacuum is determined for quasi-particles, and nuclear wave function can be described in terms of small number of quasiparticles degrees of freedom. Calculations in the framework of QRPA revealed, that the $2\beta 2\nu$ -decay rates could be strongly suppressed by taking into account the ground state correlation in nuclei which are enhanced by the particle-particle interaction. Predicted $2\beta 2\nu$ -decay rates are found to be very sensitive to the value of the strength of the particle-particle interaction g_{pp} , and calculated half-lives can be tuned to all experimental data in region of $g_{pp} \sim 1$.

Tendious calculations of matrix elements in shell model and drastic sensitivity of $2\beta 2\nu$ -decay rates on the value of g_{pp} in QRPA stimulated the development of alternative approaches. In OPE model [Hir94] the intermediate 1^+ energy spectrum is not explicitly used in calculation of $2\beta 2\nu$ -decay amplitude. The dependence of g_{pp} is high reduced and 2ν nuclear matrix elements become comparatively constant in physical region of g_{pp} .

Isotope	Shell Doi81	model Hax84	QRPA Sta90	QRPA Sta90	OEM Hir94	Rum96	Experiment
Ca^{48}	$4.0 \cdot 10^{20}$	$2.9 \cdot 10^{19}$					$4.3 \cdot 10^{19}$ Bal96
Ge^{76}	$1.3 \cdot 10^{22}$	$4.2 \cdot 10^{19}$	$8.2 \cdot 10^{20}$	$3.0 \cdot 10^{21}$	$2.6 \cdot 10^{20}$	$5.0 \cdot 10^{21}$	$1.1 \cdot 10^{21}$ Avi96 $1.8 \cdot 10^{21}$ Kla96
Se^{82}	$2.7 \cdot 10^{20}$	$2.6 \cdot 10^{19}$	$3.0 \cdot 10^{19}$	$1.1 \cdot 10^{20}$	$8.5 \cdot 10^{19}$	$2.6 \cdot 10^{20}$	$1.1 \cdot 10^{20}$ Ell92
Mo^{100}			$1.2 \cdot 10^{17}$	$1.3 \cdot 10^{18}$	$3.6 \cdot 10^{19}$	$4.1 \cdot 10^{18}$	$1.0 \cdot 10^{19}$ Das95
Te^{128}		$8.8 \cdot 10^{22}$	$7.2 \cdot 10^{23}$	$2.6 \cdot 10^{24}$	$2.1 \cdot 10^{23}$	$4.1 \cdot 10^{23}$	$7.7 \cdot 10^{24}$ Ber93
Te^{130}		$1.7 \cdot 10^{19}$	$5.9 \cdot 10^{20}$	$1.8 \cdot 10^{20}$	$7.9 \cdot 10^{19}$	$9.4 \cdot 10^{19}$	$2.7 \cdot 10^{21}$ Ber93
Xe^{136}			$1.4 \cdot 10^{21}$	$4.6 \cdot 10^{21}$	$1.0 \cdot 10^{21}$	$1.0 \cdot 10^{20}$	$> 5.5 \cdot 10^{20}$ Far96
Nd^{150}			$1.9 \cdot 10^{18}$	$7.4 \cdot 10^{18}$	$1.7 \cdot 10^{19}$	$2.0 \cdot 10^{18}$	$1.9 \cdot 10^{19}$ Art95
U^{238}			$5.2 \cdot 10^{22}$	$1.5 \cdot 10^{23}$	$9.1 \cdot 10^{20}$		$2.0 \cdot 10^{21}$ Tur91

Table 1. Predictions of $2\beta 2\nu$ -decay rates and experimental results (years).

OEM assumptions are criticised in [Eng92], as generating too small values of nuclear matrix elements. Instead, another approach eliminating the explicit summation over intermediate states, is proposed for exact evaluation of Green's function. Calculations were made only for ^{48}Ca .

Last time, there is appeared the work [Rum96]. It is claimed, that calculations for $2\beta 2\nu$ -decay rates can be made using the approximate spin-isospin symmetry without free parameters.

At the table 1 there are presented the calculations made during long time, which used many different methods. At last column its are presented the experimental positive results for $2\beta 2\nu$ -decay of the different isotopes. The predictions have changed in 10-100 times.

QRPA calculations of 0ν rates are comparably insensitive to various types of the ground state correlation (particle-particle correlation in particular). This is because in neutrinoless mode the transition are possible not through intermediate states with $J=1^+$ only, but mainly through another multipoles J^π , whose corresponding matrix elements are much less affected by change of g_{pp} [Sta90]. Most of the authors agree that comparably certain computation of $2\beta 0\nu$ -decay rates are possible. But it was so up to 95. Pantis et al. [Pan96] took in account the neutron - proton pairing and obtained the drastical reduction in half-life times, 10 times for most isotopes and 10^3 times for ^{100}Mo isotope [Pan96]

Isotope	Sh.Mod Doi81	QRPA Tom91	QRPA Sta90	OEM Hir94	out np Pan96	with np Pan96	Experiment, lower limit
Ca^{48}	$8.8 \cdot 10^{23}$				$2.5 \cdot 10^{24}$	$2.8 \cdot 10^{25}$	$9.5 \cdot 10^{21}$ Key91
Ge^{76}	$1.4 \cdot 10^{24}$	$1.9 \cdot 10^{24}$	$2.3 \cdot 10^{24}$	$2.7 \cdot 10^{24}$	$3.6 \cdot 10^{24}$	$1.8 \cdot 10^{25}$	$9.6 \cdot 10^{24}$ Kla96
Se^{82}	$2.1 \cdot 10^{23}$	$6.1 \cdot 10^{23}$	$6.0 \cdot 10^{23}$	$7.0 \cdot 10^{23}$	$1.5 \cdot 10^{24}$	$2.8 \cdot 10^{24}$	$2.7 \cdot 10^{22}$ Ell92
Mo^{100}		$2.3 \cdot 10^{23}$	$1.3 \cdot 10^{24}$		$3.9 \cdot 10^{24}$	$3.6 \cdot 10^{27}$	$4.4 \cdot 10^{22}$ Als97
Te^{128}	$6.9 \cdot 10^{24}$	$4.4 \cdot 10^{23}$	$7.8 \cdot 10^{24}$	$1.3 \cdot 10^{25}$	$1.9 \cdot 10^{25}$	$1.5 \cdot 10^{26}$	$7.7 \cdot 10^{24}$ Ber93
Te^{130}	$3.2 \cdot 10^{23}$		$4.9 \cdot 10^{23}$	$7.2 \cdot 10^{23}$	$8.6 \cdot 10^{23}$	$2.1 \cdot 10^{23}$	$2.7 \cdot 10^{22}$ Ale95
Xe^{136}			$2.2 \cdot 10^{24}$	$4.3 \cdot 10^{24}$	$1.8 \cdot 10^{24}$	$2.8 \cdot 10^{24}$	$4.4 \cdot 10^{23}$ Far96
Nd^{150}		$3.7 \cdot 10^{22}$	$3.4 \cdot 10^{22}$	$5.6 \cdot 10^{22}$			$2.1 \cdot 10^{21}$ Nel95

Table 2. Predictions of $2\beta 0\nu$ -decay rate and experimental upper limits (years).

The results of $2\beta 0\nu$ -decay rates calculations for $\langle m_\nu \rangle = 1.0$ eV are presented at the Table 2. We can conclude, that $2\beta 0\nu$ -decay investigations of the different isotopes are very important, because the calculations of nuclear matrix elements aren't very confident.

4. Geochemical experiments. Tellurium system.

There are two classes of the 2β -decay experiments: a) direct experiments, where emitted electrons are registered, b) undirect ones - geochemical and radiochemical experiments.

2β -decay products, the daughter atoms, are registered in the geochemical and radiochemical experiments. ^{82}Se , ^{128}Te , ^{136}Te isotopes were studied in geochemical experiments, because the daughter atoms were the noble gas atoms, which could be registered by mass spectrometer.

The advantages of the geochemical experiments are the possibility to have very long exposition time, $\sim 10^9$ years - the age of the ores. The main disadvantage of this method is that, it cannot directly determine the 2β -decay mode, but only the sum of the all contributing decay channels.

There were made many experiments during 50-90 years. First observation of 2β -decay (the most rare process in the world) was carried out in the geochemical experiments [Ing50].

The system of the two tellurium isotopes had been investigated many times due to its very unique features. The rather large difference in their decay energies simplifies the analysis. The transition energies for the isotopes ^{128}Te and ^{136}Te are equal to 0.87 MeV and 2.53 MeV correspondingly. The $2\beta 2\nu$ -decay rate is proportional to Q^{11} (Q is transition energy), and $2\beta 0\nu$ -decay rate is proportional to Q^5 . So $2\beta 0\nu$ process varies somewhat less rapidly. This implies that the relative contribution of $2\beta 0\nu$ -decay to ^{128}Te decay is much larger, than to ^{136}Te decay for reasonable values of $\langle m_\nu \rangle$.

The decay of ^{136}Te was well established, but there has existed a long-standing controversy over existence of ^{128}Te decay, from positive result claimed by Missouri group [Hen75,78] to negative result obtained by Heidelberg group [Kir83].

Most theoretical models predict well the ratio of $2\beta 2\nu$ half-lives for these two isotopes, despite the inaccuracy of absolute $2\beta 2\nu$ -decay rate calculations. This ratio is equal to

$$R_{th} = T_{1/2}^{2\nu}(^{136}\text{Te}) / T_{1/2}^{2\nu}(^{128}\text{Te}) \geq 2 \cdot 10^{-4}$$

Commonly, it was tempting to ascribe any difference between R_{exp} for the total half-lives and predicted R_{th} for $2\beta 2\nu$ -decay rates, as the presence of neutrinoless decay channels in ^{128}Te decay. If neutrinoless decay doesn't exist, so $R_{\text{exp}} = R_{\text{th}}$.

Last work [Ber93] confirmed the 2β -decay of ^{128}Te isotope, there were obtained the half-lives for both isotopes $T_{1/2}(^{130}\text{Te}) = (2.7 \pm 0.1) \cdot 10^{21}$ years, $T_{1/2}(^{128}\text{Te}) = (7.7 \pm 0.4) \cdot 10^{24}$ years and also the ratio $R_{\text{exp}} = (3.52 \pm 0.11) \cdot 10^{-4}$, which is in fair agreement with prediction. At this work there was made only conservative estimation on ^{128}Te neutrinoless decay, using the result obtained for ^{128}Te total half-life

$T_{1/2}^{0\nu}(^{128}\text{Te}) > (7.7 \pm 0.4) \cdot 10^{24}$ years, and very stringent limit on neutrino mass was obtained, using the QRPA calculation [Sta90], $\langle m_\nu \rangle < (1.0 - 1.5)$ eV.

In 1996 Takaoka et al. obtained the new result to Te isotopes, which are few disagreement with [Ber93].

5. Sensitivity of the direct experiments.

The $2\beta 0\nu$ -decay can be searched mainly in the direct experiments, where two electrons emitted by 2β -decaying source are registered.

The most important experimental outcome in $2\beta 0\nu$ searches is the lower bound on the neutrino mass. The $2\beta 0\nu$ absence will provide only an upper limit for $\langle m_\nu \rangle$.

$$\langle m_\nu \rangle_{\text{exp}} \leq m_e / (F_N T_{1/2}^{0\nu})^{1/2} \text{ eV},$$

where $T_{1/2}^{0\nu}$ is an experimental half-life limit, $F_N = G^{0\nu}(\mathbf{Q}) |M^{0\nu}|^2$ is the nuclear factor of merit, $G^{0\nu}(\mathbf{Q})$ is the phase space integral, and $M^{0\nu}$ is the nuclear matrix element. Phase space integrals $G^{0\nu}(\mathbf{Q})$ and the nuclear factor of merit F_N for the several isotopes, relative ^{76}Ge isotope, are presented on the Fig.8 (a,b). QRPA technique was used to calculate the matrix element, F_N changes in the range $(10^{-14} - 10^{-13}) \text{ yr}^{-1}$. One can see, that the best isotope for neutrinoless search is ^{150}Nd isotope.

At the laboratory the neutrinoless double beta decay should appear as a "gaussian -shaped" peak at the transition energy in two-electron summed energy spectrum. The example of the spectrum from Ge-detector is presented on the Fig 9. The arrow is positioned on the transition energy, the form of the peak (width of the window Γ) is connected with resolution of the detector. The sensitivity, half-life time, which can be reached, in the experiment can be written

$$T_{1/2}^{0\nu} = \ln 2 N_{2\beta} \varepsilon (t / S),$$

where $N_{2\beta}$ is a number of 2β -atoms, ϵ is an efficiency, t is a measurement time [years], S is a "signal", it is equal to the counts in the window Γ [keV], connected with resolution. If peak is absent, so "signal" can be estimated as a fluctuation of the background,

$$S \rightarrow (S)^{1/2} = (M B \Gamma t)^{1/2},$$

where M is mass of the source [kg], B is very important characteristic of the detector - the differential background, expressed in [counts/(kg keV year)].

$$N_{2\beta} = M \cdot 10^3 a N_a / A,$$

here a is an isotopic abundance, N_a is Avogadro number, A is atomic weight. We obtain the expression for sensitivity of the detector

$$T_{1/2}^{0\nu} = \ln 2 a / A \cdot 10^3 N_a \epsilon (M t / B \Gamma)^{1/2}.$$

Sensitivity is proportional to isotopic abundance a , and depends from the mass of the sample only as root square. The enrichment of the Ge-detector by isotope ^{76}Ge to 85% is equivalent to increasing of the detector mass in 100 times. The half-life limit changes slow with measurement time, only as $(t)^{1/2}$, and the bound on the neutrino mass improves very slow with the mass of the sample and time.

$$\langle m_\nu \rangle_{\text{exp}} \sim (T_{1/2}^{0\nu})^{-1/2} \sim (B / M)^{1/4}.$$

Fig.10 presents the dependence of the neutrino mass limit versus the product of the sample mass on the measurement time for different enrichment of Ge-detectors by ^{76}Ge isotope and various level of the background. There are shown the best result, obtained with natural Ge-detectors [Cal90], the limit obtained in first experiment with detector enriched by ^{76}Ge isotope [Vas90], and the best modern result for neutrino mass, carried out in the work [Kla96]. The lower line is limit, which can be obtained in the ideal case - zero background.

We can conclude that :

1. It is necessary to use the source, with high enrichment by the investigated isotope.
2. The background must be so small, as it is possible.

6.1 Calorimetric type experiments. Ge-detectors.

Direct double beta decay experiments can be divided on two large classes (Fig.11) : a) with active source (source is equal to detector) ; b) source isn't equal to detector. The second group is divided on two subgroups. Of course, it is possible some crossing between all these groups.

In the first class experiments the 2β process is identified usually only on the basis of the distribution on the two electron total energy. These calorimetric type experiments are most sensitive to neutrinoless $2\beta 0\nu$ -decay.

In the second class there is possible to have more complicated information, to measure the energy of the both electrons, some time coincidence. Such sort of information can be very useful for the rejection of the background.

Full information about 2β events can be obtained only in the track experiments. The determinations of the energy of both electron, vertex, angles, identification of the particles give the possibility to suppress the background (the main problem in 2β search) with very high efficiency.

The experiments with Ge-detectors still dominate in the search for $2\beta 0\nu$ -decay. High purity (eliminating the U and Th decay chains), excellent energy resolution provide the success for Ge-detectors. The comparison of the few best Ge experiments is presented in the Table 3.

First one is the experiment carried out by Caldwell et al. [Cal90]. They worked with 8 large Ge-detectors with natural composition of isotopes during the long time. Also there was used the active anti-Compton shielding from NaJ crystals. Their final limit on half-life is $\sim 10^{24}$ years and limit on the neutrino mass is $\langle m_\nu \rangle < 1.4 \text{ eV}$.

Second experiment is the first one with Ge-detector enriched by ^{76}Ge isotope to 85%, carried out by ITEP- YePI group [Vas90]. This group worked with two small Ge-detectors. The level of the background was a few worse than in the previous experiment and small statistic was obtained. But due to high enrichment they obtained the same result, as Berkeley group [Cal90].

M [kg]	a %	mol Ge ₇₆	Mt [kg yr]	B [kevkgy] ⁻¹	Compt shielding	T _{1/2} ^{0ν} yr lower limit	Ref.
6.9	7.8	7.0	22.6	1.2	NaJ (TI)	1.0*10 ²⁴ (90%)	Cal 90
1.18	85	13	1.0	2.2	NaJ (TI)	0.9*10 ²⁴ (90%)	Vas 90
11	85	123	17.17	0.2	—	1.0*10 ²⁵ (90%)	Kla 96
	85		2.6	0.15	—	5.7*10 ²⁴ (90%)	Avi 96

Table 3. Comparison of the best Ge-experiments.

The best modern experiment to search for $2\beta 0\nu$ decay is the experiment of Moscow-Heidelberg (KIAE-MPIH) collaboration. 5 large Ge-detectors with 85% enrichment in ^{76}Ge isotope were developed. Total mass is equal to 11 kg. Detectors were worked in the powerful passive shielding. Experiment is carried out in underground Gran-Sasso laboratory. Very ancient lead from Spain galleons were used in the passive shielding. Energy resolution is 0.2% at 2.6 MeV. The background index is very low, the large statistic was obtained. This group has the best limit on neutrinoless double beta decay and the best bound on neutrino mass $\langle m_\nu \rangle < 0.5\text{eV}$. Experiment is continued now [Kla96].

The second experiment is IGEX experiment (ITEP, INR -Russia, Spain, USA collaboration) [Avi96]. They have a few worse result for $2\beta 0\nu$ -decay, than KIAE-MPIH collaboration.

There is some contradiction between the results on $2\beta 2\nu$ -decay, obtained by these two groups. IGEX claimed, that $T_{1/2}^{2\nu}(^{76}\text{Ge}) = (1.10 \pm 0.15) \cdot 10^{21}$ years, which is in good agreement with first result of ITEP group [Vas90]. The result of KIAE-MPIH group is equal to

$$T_{1/2}^{2\nu}(^{76}\text{Ge}) = (1.77 \pm 0.12) \cdot 10^{21} \text{ years. Both results have been presented on Neutrino '96.}$$

The other isotope, which used as an active source, is ^{136}Xe isotope. The neutrinoless double decay searches were made with various methods. There were explored $2\beta 0\nu$ -decay in the liquid Xe scintillation counter [Bar86], high pressure ionisation chamber [Bar89]. The best result for Xe in calorimetric technique was obtained in Gran-Sasso experiment [Bel91] with multicell proportional counter. It was used Xe with 60% enrichment by ^{136}Xe isotope. The energy resolution was equal to 5%. Half-life limits

$T_{1/2}^{0\nu}(^{136}\text{Xe}) \geq 1.2 \cdot 10^{22}$ and $T_{1/2}^{2\nu}(^{136}\text{Xe}) \geq 1.6 \cdot 10^{20}$ years were obtained. The bound on neutrino mass was $\langle m_\nu \rangle < 13.6 \text{ eV}$ (95% CL).

The second promising technique is cryogenic thermal detector, developed by group prof. Fiorini [Ale95]. There was grown up TeO_2 crystal, which worked at very low temperature (5.5 mK). The resolution for such crystal is equal to 0.7% , what is a few worse, that one can wait theoretically. Half-life limit on neutrinoless decay

$T_{1/2}^{0\nu}(^{130}\text{Te}) \geq 2.1 \cdot 10^{22}$ years and the limit on neutrino mass $\langle m_\nu \rangle < 4.8 \text{ eV}$ (CL90%) were obtained with 334 g crystal. This group have prepared now 4 crystals from natural Te, and they also suppose to use two crystals, enriched by ^{130}Te and ^{128}Te isotopes, developed at KIAE, to test the results of geochemical experiments.

Some attempts were made to prepare the scintillation detectors from the various materials.

CdWO_4 scintillator was used to reach the high sensitivity for ^{116}Cd isotope [Geo95]. The experiment was made in Solotvino salt mine, and very good level of the background was obtained ($B=0.57$ ev/keV kg yr). The high enrichment in isotope ^{116}Cd with moderate resolution ($\Delta E=7.5\%$) yielded the half-life limit $T_{1/2}^{0\nu}(^{116}\text{Cd}) \geq 2.9 \cdot 10^{22}$ years and $\langle m_\nu \rangle < 4.6$ eV (90% CL).

^{48}Ca isotope always attracted attention by its very large transition energy. But obtaining of the samples with high enrichment is too expensive, so it was made few attempts to grow the scintillation detector from materials with natural isotopic composition. In the last work [Key91] it was used the CaF_2 crystal, containing 43g of ^{48}Ca isotope. Half-life limit

$$T_{1/2}^{0\nu}(^{48}\text{Ca}) \geq 9.5 \cdot 10^{21} \text{ years (76\% CL) was reached.}$$

At the end of this part the examples of background spectra for Ge and Te detectors are presented on the Fig. 12. One can see that, any calorimetric detector cannot compete with the Ge-semiconductor detectors.

6.2 Source isn't equal to detector.

We can apply to this group the experiments, when the passive source - the thin layers of isotope (the powder or the foil) are surrounded by some detectors (as rule the scintillation counters). There were used plastic scintillators, NaJ- and CsJ -detectors, Si(Li) semiconductor detectors, emulsions. Many different isotopes were investigated: ^{100}Mo , ^{150}Nd , ^{116}Cd , ^{136}Te . The masses of isotopes were (50-300) g. The sensitivity of the experiments to neutrinoless decay is in the range $T_{1/2}^{0\nu} \approx (10^{19} - 10^{21})$ years. Some positive results on $2\beta 2\nu$ - decay were obtained on the level $T_{1/2}^{2\nu} \approx (10^{18} - 10^{20})$ years.

For example, two wafer stacks from Si(Li)- detectors were used with Mo foil [Als97]. The sample, enriched in isotope ^{100}Mo to 97%, containing 60g, exposed in the first stack. Second stack contained natural Mo foil. Half life limit for neutrinoless decay, an upper limit on neutrino mass, and the $2\beta 2\nu$ half-life time were obtained.

$$T_{1/2}^{0\nu}(^{100}\text{Mo}) \geq 4.4 \cdot 10^{22} \text{ years, } \langle m_\nu \rangle < 9.3 \text{ eV, (68\% CL),}$$

$$T_{1/2}^{2\nu}(^{100}\text{Mo}) = (0.76 \pm 0.22_{\pm 0.14}) \cdot 10^{19} \text{ years.}$$

7. Track experiments. Three best track experiments.

First track experiment was made by Wu et al. in 1970 [Bar70]. It was investigated two isotopes, ^{48}Ca and ^{82}Se , with strimer chamber in the magnetic field. During the passed years many different tracks methods were suggested, from the cloud chamber to Time Projection Chamber, worked both with passive and active sources. I want to discuss only the last, most successful experiments.

7.1. Irvine TPC experiment.

The professor Moe group from Irvine, built TPC in magnetic field to study 2β -decay of the different isotopes [Ell88]. First work of this group was made with cloud chamber and was wrong. Schematic view of TPC and detector assembly are presented on the Fig.13(a, b). Two electron from one point in the source, arranged in the centre of TPC, were registered. The energy was determined by the shape of the trajectory. Energy resolution depended strongly from the angel relative the magnetic field and the electron energy, and changed in the range (8-15)%.

The background could be divided on two parts: internal and external. The internal background was connected with the radioactive impurities in the sources. The background was arisen mainly of the decay of ^{214}Bi and ^{208}Tl from ^{238}U and ^{232}Th chains. These atoms have the very complex decay schemes. The β -decay followed by the internal conversion electron could imitate the 2β -event. The background events could be eliminated by α -particle flagged from the following Po-decay from the same point in the source. The authors estimated the internal background as negligible. The external background caused by double Compton and Compton-Meller scattering of the external γ -quantum in the source. This background was estimated by calculations.

The example of two electrons event is presented on the Fig.13(c). Up to now there were investigated four isotopes. The results are presented in the Table 4. The best result was obtained for ^{82}Se isotope, it is in the good agreement with the geochemical result.

Half- life times for the $2\beta 2\nu$ -decay of ^{100}Mo and ^{150}Nd isotopes are in some disagreement with the measurements of the other groups, but these results didn't published up to now [Nel95]. The first positive observation of the ^{48}Ca $2\beta 2\nu$ -decay was obtained in [Bal96].

The small samples of isotopes with high enrichment were used in TPC. Very thin sources were manufactured to have the high escape probability of the α -particle from the source.

Isotope	M [g]	$T_{1/2}^{2\nu}$ [yr]	$T_{1/2}^{0\nu}$ [yr] lower limit	$\langle m_\nu \rangle$ eV upper limit	Ref.
^{82}Se	14	$(1.1 \pm_{0.1}^{0.3}) * 10^{20}$	$2.7 * 10^{22}$ (68% CL)	4.7	Ell92
^{100}Mo	8.3	$(7.1 \pm 0.9) * 10^{18}$	$1.12 * 10^{21}$ (68% CL)	33.8	Nel95
^{150}Nd	13	$(6.6 \pm 1.5) * 10^{18}$	$1.1 * 10^{21}$ (68% CL)	5.55	Nel95
^{48}Ca	42	$(4.3 \pm_{1.1}^{2.4}) * 10^{19}$			Bal96

Table 4. Results of Irvine TPC experiment.

So, it is difficult to increase the mass of isotopes at the TPC detector and to improve the limit for neutrinoless double beta-decay.

7.2 NEMO experiment.

The next successful track experiment is NEMO-2 [Arn95]. Currently NEMO collaboration (France, Russia, Ukraine, USA) is building a large detector to utilize 10kg of an enriched Mo (molybdenum) source. NEMO-2 detector was developed to test the method and to study the background processes. Schematic view of NEMO-2 detector is presented at the Fig.14(a). The experiment was located in the Frejus Underground laboratory. A thin source (1m^2 foil) was housed in the centre of the detector. The information about the tracks of two electrons, emitted from the source, recorded in the drift chambers, composed by Geiger cells. Two scintillator arrays was devoted to energy and time-of-flight measurements.

The background rejection realised by time-of-flight measurements. Two electrons from the central source must have the same times for two counters. The background event with a single electron from the lateral cover, crossing detector, would have the different times. The examples of events in the detector are shown at the Fig.14(b): first is the electron, crossing detectors from left to right with scattering in the source, second is the event with two electrons from the central foil. Energy resolution was $\text{FWHM} = (28E + 2300)^{1/2}$ [keV], it corresponded to $\Delta E/E=17.4\%$ for 1 MeV and one can wait $\sim 10\%$ resolution for 3 MeV sum-energy of two electrons (transition energy). The time resolution was equal to 275 psec for 1 MeV electron.

The source was divided in two part. First part with mass 172 g was enriched by ^{100}Mo isotope to 98.4%, the second one was from natural Mo and contained about 16 g of ^{100}Mo . The subtraction procedure was used to eliminate the external background.

The radioactive contamination in the foil were checked by low background Ge- spectrometer. The estimations have shown, that internal background was negligible.

Up to now NEMO investigated the 2β -decay for the few isotopes. The data, obtained with NEMO-2 detector are presented in the Table 5.

Isotope	M [g]	$T_{1/2}^{2\nu}$ [yr]	$T_{1/2}^{0\nu}$ yr lower limit	$\langle m_\nu \rangle$ eV upper limit	Ref.
$^{100}\text{Mo}^{82}$	169	$(0.95 \pm 0.04 \pm 0.09) * 10^{19}$	$6.4 * 10^{21}$ (90 % CL)	14	Das95
^{116}Cd	137.7	$(3.75 \pm 0.35 \pm 0.21) * 10^{19}$	$5.1 * 10^{21}$ (90 % CL)	9.8	Arn96
^{82}Se	152.2	$(1.2 \pm 0.3 \pm 0.2) * 10^{20}$	$3.6 * 10^{21}$ (90 % CL)	12.9	Arn97
^{96}Zr	6.8	$(\sim 3.5 \text{ or } >2) * 10^{19}$	$5.5 * 10^{20}$ (90% CL)	31	Arn97

Table 5. The results of NEMO experiment.

The best result is 2ν half-life for ^{100}Mo . The $2\beta 2\nu$ positive results give the possibility to check the calculations of the nuclear matrix elements.

Fig.15 shows the artistic view of the future NEMO-3 detector. It will be completed from the 20 separate towers with the Geiger tubes and the arrays of the scintillation counters. The source, 20 m^2 foil, will be housed in the centre and can contain up to 10 kg of the different isotopes. The goal of the future experiment is to reach sensitivity 10^{25} years for neutrinoless double beta decay. It may be some problem with the background from the $2\beta 2\nu$ -decay in the window of $2\beta 0\nu$ decay, which will enhance due to the moderate energy resolution. One tower is completed now and tested.

7.3 Gotthard TPC for 2β search in ^{136}Xe .

Very sensitive search for neutrinoless 2β decay was carried out in the Gotthard Underground laboratory. The schematic view of time projection chamber detector is presented on Fig.16(a). TPC with an active volume of 180 l was filled by ^{136}Xe (enrichment 62.5%) at 5 atmosphere

[Vui93]. Total mass of ^{136}Xe isotope was more than 3kg. Secondary electrons produced by primary ionization are drifted in the uniform electric field to the anode wires, where charge multiplication occurs. Signals electrostatically induce at nearby xy- readout plane. The time evolution of the signals gives the information in z-direction. In this way three-dimensional track reconstruction is achieved. The energy of events is measured by integrating the anode signals over the drift time. The simultaneous tracking and calorimetric capabilities of the TPC make it an ideal device to study 2β -decay in the ^{136}Xe .

A 2β -decay event is identified as a continuous trajectory with characteristic "end features": high-charge depositions (charge "blobs"), due to enhanced dE/dx at low energy and large-angle multiple scattering at the both ends. This provides a powerful means of background suppression from α -particles, cosmic muons, single electrons. The examples of the events in TPC are shown on Fig16(b). The very low background index was obtained, $B=0.01$ ev/keVkg. The energy resolution was equal $\text{FWHM} = 7.5\%$ on 2.48 MeV. The results presented on 'Neutrino-96' conference, used the full statistic 1.57yr.

$$T_{1/2}^{0\nu} (^{136}\text{Xe}) \geq 4.4 \cdot 10^{23} \text{ years}, \quad \langle m_\nu \rangle < 2.9 \text{ eV},$$

$$T_{1/2}^{2\nu} (^{136}\text{Xe}) \geq 5.5 \cdot 10^{20} \text{ years (90\% CL)}.$$

It is second best limit on the neutrinoless decay and neutrino mass, obtained in the direct experiments.

8. ITEP track experiment.

ITEP is preparing now the large track experiment (TPC in the magnetic field) to search for the neutrinoless double beta decay of the different isotopes: ^{136}Xe and ^{150}Nd [Art91].

Schematic view of set-up is presented on Fig.17. The electrons from 2β -decay of ^{136}Xe , occurred in the central part of TPC, registered in two adjacent volumes, separated by thin mylar film. These two volumes are filled by methane in order to reduce the multiple scattering of the low energy (0.3-2.0 MeV) electrons. TPC is positioned in magnetic field for increasing acceptance and measuring energy. The coordinates are measured with proportional cells, arranged at the centre of the TPC. Number of the cell is the coordinate along the magnetic field, the drift time gives the coordinate along the electric field. The analysis of the helix trajectory parameters gives the energy and the sign of the electrons. Also the ionization losses in Xe may be measured.

TPC size is (3m*3m*1.5m). It works at atmospheric pressure and can utilise up to 10kg of Xe. In the case of ^{150}Nd isotope, the solid source will be located on mylar film, separated two volumes.

TPC is surrounded by proportional counters of the active protection from cosmic radiation.

8.1 $2\beta 2\nu$ -decay study with small TPC.

For testing the method and studying the background small TPC was constructed and installed in the magnet MS-12 in the accelerator hall (Fig.18). We have investigated $2\beta 2\nu$ -decay of ^{136}Xe [Art92] and ^{150}Nd [Art95] in this detector. TPC dimensions are (1.0m*0.8m*0.4m). From three sides TPC are surrounded by antic cosmic counters. TPC has two gas volumes. Small volume was filled by the mixture of Xe and CH_4 , or by methane in case of Nd solid source, which was located on the mylar film. High voltage electrode was arranged on the one side of TPC, two multiwire detectors were located on the opposite one. The detector for the large volume contained 30 sensitive wires and additional readout from the cathode strips, arranged to 45° respect to the direction of the sense wires. The energy of electrons were measured by the form of the trajectory in the magnetic field. Fig. 19 shows the example of the electron track from radioactive source ^{90}Sr . The main projection is the sign, the strip projection is cycloid and its sharp part gives the direction (or the sign) of the electron.

Energy resolution was determined with the radioactive source ^{207}Bi (Fig.20) and was equal to $\Delta E = \pm 100 \text{ keV}$ for two electron lines (0.5MeV and 1.0MeV). The estimation showed, that ununiformity of the magnetic field deteriorated resolution twice as much.

The detector geometry was oriented on the registration of the events, when both decay electrons emitted from the source in the same direction. The topology of typical events are shown on Fig.21. The main part of the events had two track of the opposite helicity: the electron from upper cover reflected in the target (b), e^+e^- -pair produced in the source (b). These events had rejected easily by the shape of their trajectories in the strip projection.

Two other types of the background events cannot be rejected, using only the track information. First one is connected with internal radioactive impurities from ^{238}U and ^{232}Th chains in the target. The ^{214}Pb , ^{214}Bi and ^{208}Tl isotopes have the very complicate decay scheme, so β -decay followed by internal conversion electron can imitate 2β -decay (d). We made additional measurements to estimate the internal background.

Second type is caused by the external γ -radiation flux, double Compton and Compton- Meller scattering in the source (e). To eliminate external background we exposed simultaneously two sources (one was enriched by ^{150}Nd isotope and contained 40g, other sample was with natural isotopic composition and had only 2.5g). The subtraction would be right, if the internal background was small. From ^{238}U series the main dangerous was from ^{214}Bi isotope, because it has large transition energy and high conversion coefficients. α -decay of ^{214}Po followed the ^{214}Bi -decay with half-time 164 μsec . Our detector worked in proportional mode, we can separate α -particle with energy 8 MeV from electron by its ionization signal. In the additional runs we searched (β - α)-delayed coincidence. The arrival time distribution of the delayed α -particle for ^{150}Nd source is shown on the Fig.22(a). The distribution was collected during 60 hours. Then we made the special calibrated sources, polluted by ^{238}U and ^{232}Th isotopes with well known concentration. Second distribution, presented on Fig.22(b), is for the source with ^{238}U and was collected during 1.1 hour. Very distinctive peak with character time 164 μsec is determined. There were selected also 2 β -events for this calibrated source, Fig.22(c). We can obtain the limit on the background events in our working source, using the ratio of 2 β /(β - α) events for calibration source, polluted by ^{238}U . The similar measurements were made for all our working and calibrated sources to estimate the background from the isotopes of ^{232}Th series. It was obtained that internal background is small, and the subtraction procedure was correct.

Sum-energy spectra of two electrons for ^{150}Nd source and for the source with natural isotopic composition are presented on the Fig.23 (a, b). The signal to the background ratio is equal 4/1. The positive effect is (23 ± 6) event in the energy interval $0.9\text{MeV} < (E_1+E_2) < 2.0\text{MeV}$. The efficiency of the TPC to 2 β 2 ν -decay of ^{150}Nd was calculated by Monte-Carlo method and were checked, comparing the measurements with calculations for calibrated sources. We used these sources, as the sources of the two electrons events. Half-life for ^{150}Nd is equal [Art95]

$$T_{1/2}^{2\nu}(^{150}\text{Nd}) = [1.88 \pm 0.66_{\pm 0.39} \pm 0.19] * 10^{19} \text{ years.}$$

The result for neutrinoless double beta decay is not very good, due to small amount of the isotope, small exposition time, and the magnetic field was not optimal for neutrinoless search.

$$T_{1/2}^{0\nu}(^{150}\text{Nd}) > 1.9 * 10^{29} \text{ years, } <m_\nu> < 13 \text{ eV (90\%CL).}$$

For ^{136}Xe we obtained only the upper limit $T_{1/2}^{2\nu}(^{136}\text{Xe}) > 9.3 * 10^{19} \text{ years}$ [Art92].

The very high background suppression factor, $k > 10^7$, was obtained, from first level trigger 100 ev/sec to 10ev/ 1000 hours. Background index $B = 0.5 \text{ ev/(kg keV yr)}$ in the energy range

(0.9-2.5) MeV for ^{150}Nd was reached, the same result was also obtained for ^{136}Xe . TPC worked in the conditions of the ordinary earth laboratory.

We wait, that this index B will be reduce more than 10 times in the region of the transition energy for both isotopes (^{136}Xe - 2.48 MeV, ^{150}Nd - 3.37 MeV).

8.2 Status of large TPC.

Set-up was assembled. The magnet, TPC, 280 proportional counters of an active protection from charge cosmic radiation were located on the worked place. Three multiwire detectors were tested with radioactive sources and were installed in TPC. Magnetic measurements were performed. The measurements are agreed well with calculations. The uniformity of the magnetic field is $\sim 1.5\%$ for $R < 1.5\text{m}$, and better than 4.5% for $R < 2.5\text{m}$. Now we are finishing the gas system.

In the table 6 there is presented the comparison of the two TPC detectors [Art96].

	Small TPC $V = 0.3 \text{ m}^3$	Large TPC $V = 13 \text{ m}^3$
Number of gas volumes	2	3
Number of drift gaps	1	2
Max. drift length	0.8 m	1.5 m
Magnetic field	0.7 kGauss	1.0 kGauss
Number of anode wires	40	260
Number of cathode stripes	44	980
Max. amount of isotopes	500g - ^{136}Xe , 50g - ^{150}Nd	7.5kg - ^{136}Xe , 5kg - ^{150}Nd
Energy resolution	100keV for 1Mev (exp.)	(3-4)% for 2.5MeV (MC cal.)
Efficiency	2.8% ($2\beta 2\nu$), cal., exp.	(20-40)% ($2\beta 0\nu$), (MC cal.)
Results and sensitivity	^{136}Xe $T_{1/2}^{2\nu} > 9.3 \cdot 10^{19} \text{ yr.}$ ^{150}Nd $T_{1/2}^{2\nu} = 1.9 \cdot 10^{19} \text{ yr.}$	$T_{1/2}^{0\nu} \geq (2-4) \cdot 10^{24} \text{ yr.}$ expected

Table 6. Comparison of the two TPC.

We have 10 kg of ^{136}Xe isotope with 95% enrichment, also we hope to obtain the (5-8) kg of ^{150}Nd isotope.

We estimate our sensitivity to $2\beta^{0\nu}$ -decay, on the basis of the work with prototype, as $T_{1/2}^{0\nu} > (2-4) \cdot 10^{24}$ years. So, the limit on neutrino mass $\langle m_\nu \rangle < (0.6-0.5)$ eV can be reach.

Fig.24 is shown the artistic view of the large TPC. There are shown three gas volumes, three separate multiwire detectors. The resolution, calculated by Monte Carlo method, for the large TPC is presented on the Fig.25.

9. Future of 2β -decay study. Liquid Xenon Detector.

In all modern working experiments and experiments under construction are used or supposed to use about 10kg of the different isotopes. KIAE-MPIH collaboration are working with 11kg of ^{76}Ge -isotope, IGEX collaboration now have 7 kg ^{76}Ge in their detectors, NEMO-3 supposes to utilize 10 kg of ^{100}Mo isotope, ITEP track experiment can use up to 10kg of ^{136}Xe and ^{150}Nd isotopes. It is very difficult to increase strongly the mass of isotopes in all these set-ups.

Such amount of isotopes are corresponded to $N_{2p} = (3-10) \cdot 10^{25}$ atoms. So we can wait, that it will be possible to reach the sensitivity on half-life $T_{1/2}^{0\nu} \sim 10^{25} - 5 \cdot 10^{25}$ years. Limit on the neutrino mass improved very slow with the mass of the isotope, $\langle m_\nu \rangle \sim (B/M)^{1/4}$.

Next step in double β -decay study must be connect with the other idea. There are some motivations for using liquid xenon (LXe) detector.

1. Large mass isotope in the small volume. 2. Confining of β tracks within the detector. 3. Calorimeter with the resolution better than 4.0%. 4. Possibility to reject e^+e^- pair, by flagged of the 0.511 MeV γ -quantum, and to suppress the double Compton scattering. 5. LXe provides self shielding due to the fact, that Xe is the very clear and dense material. 6. Scintillation of LXe can provide a fast trigger. 7. The enrichment by isotope ^{136}Xe is not very difficult operation.

Girard et al. suggested the large LXe detector for neutrinoless double beta decay search with sensitivity more than $T_{1/2}^{0\nu} > 10^{26}$ years [Gir92].

New idea to suppress the background was supposed [Moe91]. Background could be essentially eliminate in LXe detector, if the double beta daughter - positively ionized Ba (barium) could be detected in association with the beta particles on an event- by -event basis. Discussed detection methods include the laser-excited fluorescence and collection of the ions on an electrode for introduction into a time-of-flight mass spectrometer. Single Ba^+ ion was registered already in small volume [Neu80]. Also there were some attempts of Japan group [Miy94] to register Ba, collected on the electrode and then introduced it in the mass-spectrometer.

Success in the detecting of the Ba-ion in LXe would greatly improve the chance of the building a background free (10^2 - 10^3) kg detector, capable of detecting $\langle m_\nu \rangle$ - majorana neutrino mass, as small as $\sim 10^{-2}$ eV.

ITEP has 1.2 ton of Xe, it means that ~ 100 kg of ^{136}Xe is available.

The $2\beta 2\nu$ spectrum can limit the sensitivity of the $2\beta 0\nu$ half-life. Fig.26 shows the fraction of a resolution broadened $2\beta 2\nu$ spectrum, falling in an experimental FWHM window centred on the expected of $2\beta 0\nu$ peak. For large LXe experiment "background" from $2\beta 2\nu$ -decay must be considered. The fraction from 2ν is not more than $f < (2 \cdot 10^{-7} - 2 \cdot 10^{-8})$ for FWHM $\sim (4-6)\%$. We can wait less than (0.1-1.0) event for 1 year measurement time, if we use the new experimental limit [Far96] $T_{1/2}^{2\nu}(\text{Xe}) = 5 \cdot 10^{20}$. So for LXe detector with 100 kg of ^{136}Xe the sensitivity $T_{1/2}^{0\nu} > (0.5-1.0) \cdot 10^{26}$ years and limit on neutrino mass $\langle m_\nu \rangle < (0.5-0.1)\text{eV}$ could be reached.

On the Fig.27 there are presented the tails of $2\beta 2\nu$ -decay in the window of the $2\beta 0\nu$ peak for two detectors: for NEMO-3 and ITEP TPC. It is obviously, that this background is a some problem for both detectors, especially for NEMO.

10. Results on the neutrinoless and two neutrino double β -decays.

In table 9 there are collected the limits for neutrino mass from the most advanced experiments.

Isotope	Limit experimental $T_{1/2}^{0\nu}$ [years]	Theory QRPA [Sta90] $T_{1/2}^{0\nu} \langle m_\nu \rangle^2$ [yr*eV ²]	Upper limit $\langle m_\nu \rangle$ eV	Ref.
^{48}Ca	$9.5 \cdot 10^{21}$ (76%CL)			Key91
^{76}Ge	$1.0 \cdot 10^{24}$ (90%CL)	$2.33 \cdot 10^{24}$	0.5	Kla96
^{82}Se	$2.7 \cdot 10^{22}$ (68%CL)	$6.03 \cdot 10^{23}$	4.7	ElI92
^{100}Mo	$5.2 \cdot 10^{22}$ (68%CL)	$1.27 \cdot 10^{24}$	4.9	Eji96
^{116}Cd	$2.9 \cdot 10^{22}$ (90%CL)	$4.87 \cdot 10^{23}$	4.1	Geo95
^{128}Te	$7.7 \cdot 10^{24}$ (90%CL)	$7.80 \cdot 10^{24}$	1.1	Ber93
^{130}Te	$2.1 \cdot 10^{22}$ (90%CL)	$4.89 \cdot 10^{23}$	4.9	Ale95
^{136}Xe	$4.4 \cdot 10^{23}$ (90%CL)	$2.21 \cdot 10^{24}$	2.9	Vui96
^{150}Nd	$2.1 \cdot 10^{21}$ (68%CL)	$3.37 \cdot 10^{22}$	4.0	Nel95

Table 9. The half-life limits on neutrinoless decay and upper limits on neutrino mass.

At the Fig.28 the results for $2\beta 2\nu$ -decay investigation are presented. The arrows show the isotopes, for which the positive result was obtained. The points show the isotopes, in the investigation of which the physicists from ITEP took part.

The main conclusion : the experimental study of the neutrinoless double beta decay must be continued.

Figure 1.

Figure 2.

Figure 3.

ΔM_A , MeV ΔM_A , MeV

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

Figure 13.

Diagram of the experimental configuration. 1 - Central frame supporting the source. 2 - Copper frames which support the Geiger cells. 3 - 8×8 arrays of scintillator counters.

Figure 14.

Figure 15.

Figure 16.

Figure 17.

- 1-TPC
- 2- multiwire detectors
- 3- maylar film with Nd samples
- 4- proportional counters of the active protection from cosmic radiation
- 5- magnet coils

Solid sources - 17mg/cm² Nd₂O₃ + 8.5mg/cm² wax

Figure 18.

Figure 19.

Figure 20

Figure 21.

Figure 22.

Figure 23.

Figure 24.

Figure 25.

Figure 26.

Figure 27.

Figure 28.

Figure Captions.

- Figure 1. Feynman diagrams for: (a) $2\beta 2\nu$, (b) $2\beta 0\nu$ and (c) $2\beta 0\nu\chi$.
- Figure 2. Two electron sum-energy spectra in the cases of $2\beta 2\nu$, $2\beta 0\nu$ and $2\beta 0\nu\chi$ decay.
- Figure 3. Dependence of the atom mass ($M-A$) (defect of the mass) from the charge of nucleus (Z) for $A=135$, $A=136$ and $A=137$.
- Figure 4. Atomic mass difference between parent 2β nuclides and daughter isotopes: (a) - for parents $2\beta^-$ nuclides, (b) - for parent $2\beta^+$, $\epsilon\beta^+$ and 2ϵ nuclides.
- Figure 5. Natural abundance of 2β isotopes: (a) - for parents $2\beta^-$ nuclides, (b) - for parent $2\beta^+$, $\epsilon\beta^+$ and 2ϵ nuclides.
- Figure 6. The Majorana mass term connection.
- Figure 7. The place of $2\beta 0\nu$ investigation among the other neutrino experiments.
- Figure 8. $G^{0\nu}$ - phase space integral (a), and F^N - nuclear factor of merit (b) for the several isotopes relative Ge^{76} isotope.
- Figure 9. Two electron summed energy spectrum from Ge-detector, with expected peak at the transition energy 2038.6 keV.
- Figure 10. The minimal detectable $\langle m\nu \rangle$ versus detector mass and run time for ^{76}Ge experiments with various levels of the background and isotopic enrichment. There are presented three results from experiments: ● – the best experiment with natural detectors [Cal90], ■ – first experiment with Ge-detector, enriched by ^{76}Ge [Vas90], ▼ – the best modern experiment with enriched detectors.
- Figure 11. Classification of 2β -decay experiments.
- Figure 12. Examples of the background spectra: (a) - for Ge-detector, (b) - for TeO_2 cryogenic detector.
- Figure 13. Irvine TPC experiment: (a) - schematic view of TPC, (b) - detector assemble, (c) - example of two electron event.
- Figure 14. NEMO-2 detector: (a) - schematic view, (b) - examples of the events.
- Figure 15. Artistic view of NEMO-3 detector.
- Figure 16. Gotthard ^{136}Xe TPC: (a) - schematic view of the set-up, (b) - examples of the events.
- Figure 17. ITEP TPC with volume 13m^3 in the magnet.
- Figure 18. Schematic view of the small ITEP TPC.

Figure 19. The example of single electron event from the radioactive source ^{90}Sr .

Figure 20. The energy resolution, measured with ^{207}Bi source, two lines: 0.5 MeV and 1.0 MeV, $\text{HWHM} = \pm 100 \text{ keV}$.

Figure 21. Topology of the typical events in TPC: a) 2β -event; b) the electron from upper cover, reflected in the source; c) e^+e^- -pair production in the source; d) internal background of ^{214}Bi β -decay, followed by internal conversion electron; e) external background from double Compton and Compton-Møller scattering γ -radiation flux in the source.

Figure 22. Time distribution of delayed α -particle from ^{214}Bi - ^{214}Po cascade: (a) - for ^{150}Nd source, (b) - the same distribution for calibrated source, polluted by ^{238}U . (c) - Sum-energy spectrum of 2β events from calibrated source.

Figure 23. The sum-energy spectrum of two electrons : (a) - for the source, enriched by ^{150}Nd isotope (1260 hours, 36 events); (b) - for the source with natural isotopic composition (910 hours, 9 events).

Figure 24. Artistic view of the large TPC.

Figure 25. Expected energy resolution to ^{136}Xe $2\beta 0\nu$ -decay for large TPC, calculated by Monte Carlo method (transition energy is 2.48 MeV).

Figure 26. Fraction of the resolution broadened $2\beta 2\nu$ spectrum falling in an experimental FWHM window.

Figure 27. Tails from $2\beta 2\nu$ decay: (a) - for NEMO detector, (b) - for ITEP TPC.

Figure 28. Results for $2\beta 2\nu$ decay. The arrows mark positive results and the points show the isotopes, in the investigation of which peoples from ITEP took part.

References.

- Ale97 Alessandrello A. et al. "Improvements in ^{130}Te double beta decay search with cryogenic TeO_2 array detectors", Nucl.Phys B (Proc.Suppl.) 48, 238 (1995), TAUP'95
- Als97 Alston-Garnjost M. et al. "Experimental search for double β -decay of ^{100}Mo ", Phys.Rev. C 55, 474 (1997)
- Arn95 Arnold R. et al. (NEMO Collab.) "Performance of a prototype tracking detector for double beta decay measurements", NIM A 354, 338 (1995)
- Arn96 Arnold R. et al. (NEMO collab.) "Double β -decay of ^{116}Cd ", Z.Phys.C 72, 239 (1996)
- Arn97 Arnold R. et al. (NEMO collab.) "Double β -decay of ^{82}Se and ^{96}Zr ", 'NEUTRINO-96', Helsinki, (1996)
- Art91 Artemiev V. et al. "The ^{136}Xe double beta decay track experiment", NIM A 303, 309, (1991)
- Art92 Artemiev V. et al. "The search for ^{136}Xe $2\beta 2\nu$ -decay with a proportional drift detector", Phys.Lett. B 280, 159 (1992)
- Art95 Artemiev V. et al. "Half-life measurement for ^{150}Nd $2\beta 2\nu$ -decay in the Time Projection Chamber experiment", Phys.Lett. B 345, 564 (1995)
- Art96 Artemiev V. et al. "Track experiment for the double beta decay search of the different isotopes", Nucl.Phys B(Proc.Suppl.) 48, 241 (1995), TAUP'95
- Avi96 Avignone F.T. III "The IGEX double beta decay experiment with pulse shape discrimination", Proc. of International Workshop on Future Prospects of Baryon Instability search in p-decay and n-n-bar oscillation experiments", Oak-Ridge, Tennessee, USA, 167 (1996)
- Bal96 Balysh A. et al. "Double beta -decay of ^{48}Ca ", Submitted to Phys.Rev.Lett.

- Bar70 Bardin R.K. et al. "A search for the double beta decay of ^{48}Ca and lepton conservation" Nucl.Phys. A 158, 337 (1970)
- Bar86 Barabanov I.R. et al. "Investigation of ^{136}Xe double β -decay", Pis'ma Zh.Eksp.Teor.Fiz. 43, 166 (1986), (in Russian)
- Bar89 Barabash A.S. et al. "Results of the experiment on the search for double beta decay of ^{136}Xe , ^{134}Xe and ^{124}Xe ", Phys.Lett. B 223, 273 (1989)
- Bel91 Bellotti E. et al. "A search for two neutrino and neutrinoless double beta decay of ^{136}Xe in the Gran Sasso underground laboratory", Phys.Lett. B 226, 193, (1991)
- Ber97 Bernatowicz et al. "A Precise Determination of Relative and Absolute $\beta\beta$ decay of ^{128}Te and ^{130}Te ", Phys.Rev. C 47, 806 (1993)
- Cal90 Caldwell D.O. et al. "Review of Double Beta Decay Experiments", Nucl.Phys. B (Proc. Suppl.), 13, 547 (1990)
- Das95 Dassie D. et al. (NEMO Coll.) "Two-neutrino double β -decay measurement of ^{100}Mo ", Phys.Rev. D 51, 2090 (1995)
- Doi81 Doi M. et al. "Neutrino masses and the double β -decay", Phys.Lett. B 103, 219 (1981)
- Doi85 Doi M., Kotani T. and Takasugi E. "Double Beta Decay and Majorana neutrino", Prog.Theor.Phys.Suppl. 83, 1 (1985)
- Eji96 Ejiri H. et al. "Double Beta Decays Studied by Elegant's V & VI", 'NEUTRINO-96', Helsinki 1996
- Ell87 Elliott S.R. et al. "Direct Evidence for Two neutrino Double Beta Decay in ^{82}Se ", Phys.Rev.Lett. 59, 2020 (1987)
- Ell88 Elliott S.R. et al. "A Time Projection Chamber for Detection of Double Beta Decay", NIM A 273, 226 (1988)
- Ell92 Elliott S.R. et al. "Double Beta Decay of ^{82}Se ", Phys.Rev. C 46, 135 (1992)
- Eng92 Engel J., Haxton W.C. and Vogel P., "Nuclear structure effects in double beta decay", Phys.Rev. C 46, 2153 (1992)
- Far96 Farine J. et al. "Search for $\beta\beta$ -decay in ^{136}X . The Gotthard TPC", 'NEUTRINO-96', Helsinki
- Gel81 Gelmini G.B. and Roncadeli M., "Left-handed neutrino mass scale and spontaneously broken lepton number", Phys.Lett. B 99, 44 (1981)

- Geo95 Georgadze A.Ch. et al., "The results of 2β -decay investigation of ^{116}Cd with scintillator $^{116}\text{CdWO}_4$ ", Sov.J.Nucl.Phys. 58, 1170 (1995), (in Russian)
- Gir92 Girard T.A., Aprile E., Fernholz R.C., "Sensitivity of a large volume LXe TPC to neutrinoless double beta decay", NIM A 316, 44 (1992)
- Hax84 Haxton W.S. and Stephenson G.J. Jr., "Double Beta Decay", Prog.Part.Nucl.Phys. 12, 409 (1984)
- Hen75 Henneke E.W. and Manuel O.K., "Double beta decay of ^{128}Te ", Phys.Rev. C 11, 1378 (1975)
- Hen78 Henneke E.W., "Additional evidence for $\beta\beta$ -decay of ^{128}Te ", Phys.Rev. C 17, 1168 (1978)
- Hir94 Hirsh M. et al. "Operator Expansion Method and Nuclear $\beta\beta$ -decay", Phys.Rep. 242, 403 (1994)
- Ing50 Inghram M.G. and Reynolds J.H., "Double Beta Decay of ^{130}Te ", Phys.Rev. 78, 822 (1950)
- Key91 Ke You et al., "A search for neutrinoless double beta decay of ^{48}Ca ", Phys.Lett. B 265, 55 (1991)
- Kir68 Kirsten T. et al., "Experimental Evidence for the Double Beta Decay of ^{130}Te ", Phys.Rev.Lett. 20, 1300 (1968)
- Kir83 Kirsten T. et al., "Rejection evidence for nonzero neutrino rest mass from double beta decay", Phys.Rev.Lett. 50, 474, (1983)
- Kla96 Klapdor-Kleingrothaus H.V., "Double Beta Decay - Physics at Beyond Accelerator Energies", Proc. of International Workshop on Future Prospects of Baryon Instability search in p-decay and n-n-bar oscillation experiments", Oak-Ridge, Tennessee, USA, 125 (1996)
- Moe91 Moe M.R., "New approach to the detection of neutrinoless double beta decay", Phys.Rev. C 44, R931 (1991)
- Miy95 Miyajima M., Sasaki S., Tawara H., "Search for Double Beta-decay Products of ^{136}Xe in Liquid Xenon", KEK Preprint 94-21, 1994 H
- Nel95 Nelson M.A. "The Double Beta Decay of ^{150}Nd and ^{100}Mo ", Dissertation, University of California, Irvine, 1995, unpublished

- Neu80 Neuhauser W., Hohenstatt M. and Toschek P.E., "Localised visible B^+ mono-ion oscillator" *Phys.Rev. A* 22, 1137 (1980)
- Pan96 Pantis G. et al., "Neutrinoless double beta decay within the quasiparticle random-phase approximation with proton-neutron pairing", *Phys.Rev. C* 53, 659, (1996)
- Rum96 Rumyantsev O.A. and Urin M.G., "Approximate Symmetry in Nuclei and the $2\nu 2\beta$ -decay rate", *Izv.Rus.Akad.Nauk, ser.fiz.*, N11, 1 (1996) (in Russian)
- Sta90 Staudt A., Muto K. and Klapdor-Kleingrothaus H.V., "Calculation of 2ν and 0ν double beta decay", *Europhysics Lett.* 13, 31 (1990)
- Sch82 Schechter J. and Valle J.W.E., "Neutrinoless double beta-decay in $SU(2)\times SU(1)$ theories", *Phys.Rev. D* 25, 2951 (1982)
- Sch84 Schepkin M.G., "Double beta-decay and neutrino mass", *Uspexi Fiz. Nauk* 143, 513 (1984) (in Russian)
- Tak96 Takaoka N. et al., "Half-life of ^{130}Te double β -decay measure with geologically qualified samples", *Phys.Rev. C* 53, 1552 (1996)
- Tom91 Tomoda T., "Double Beta Decay", *Rep.Prog.Phys.* 54, 53 (1991)
- Tre95 Tretyak V.I. and Zdesenko Yu.G., "Tables of the results of 2β -decay research", KEK Preprint 95-189, 1995
- Tur91 Turkevich A.L. et al., "Double Beta Decay of ^{238}U ", *Phys.Rev.Lett.* 67, 3211 (1991)
- Vas90 Vasenko A.A. et al., "New results in the ITEP-YePI double beta-decay experiment with enriched germanium detectors", *Mod.Phys.Lett. A* 5, 1299 (1990)
- Vog86 Vogel P. and Zimbauer M.R., "Suppression of the two neutrino double beta decay by nuclear structure effect", *Phys.Rev.Lett.* 57, 3148 (1986)
- Vui93 Vuilleumier J.-C. et al., "Search for neutrinoless 2β -decay in ^{136}Xe with a time projection chamber", *Phys.Rev. D* 48, 1009 (1993)
- Wu 57 Wu C.S. et al., "Experimental Test of Parity Conservation in Beta Decay", *Phys.Rev.* 105, 1413 (1957)

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