Neutron Lifetime Experiment with a Gravitational Trap and a Low-Temperature Fomblin Coating

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Gatchina - 2004
Измерение времени жизни нейтрона с гравитационной ловушкой и с покрытием из низкотемпературного фомблина

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Мы представляем новый результат измерения времени жизни нейтрона (878.5 ± 0.7\text{stat.} ± 0.3\text{syst.}) с. Этот результат отличается от среднего мирового значения на 6 стандартных отклонений и на 4 стандартных отклонений от предыдущего наиболее точного результата [1]. Однако новое значение для времени жизни нейтрона вместе с β-асимметрией в распаде нейтрона ($A_0 = -0.1189(7)$ [2]) находится в хорошем согласии со Стандартной Моделью.

А б с т р а к т

We present a new result of neutron lifetime measurements (878.5 ± 0.7\text{stat.} ± 0.3\text{syst.}) s. This result is different from the world average value by 6 standard deviations and by 4 standard deviations from the previous most precise result [1]. However, the new result for neutron lifetime together with β-asymmetry in neutron decay ($A_0 = -0.1189(7)$ [2]) is in a good agreement with Standard Model.

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1. Introduction

The decay of the free neutron into a proton, an electron and an antineutrino is related to the weak interaction process. In the Standard Model the probability of this process or the lifetime of the free neutron is related to the vector $G_v$ and axial $G_A$ weak interaction coupling constants. The neutron lifetime has important implications in particle physics, in neutrino induced reactions and in cosmology. The neutron lifetime together with angular correlation coefficients of the decay of a polarised neutron allows to deduce the axial and vector coupling constants only from neutron decay data. The main element of Kobayashi-Maskawa matrix $V_{ud}$ has to be determined with the highest accuracy to check for eventual deviations from the standard model which are currently under discussion [3].

The observed deviation from unitarity condition for the Cabibbo-Kobayashi-Maskawa matrix is about 2.7 standard deviations. The origin of this deviation is unclear. This situation requires more precise measurements of $\beta$-asymmetry $-A$ and new measurements of the neutron lifetime.

Today, the weighed mean value of the neutron lifetime is 885.7(8) s. The accuracy of this world average was improved in the lifetime experiment of a group from KIAE, Russia [1]. This result $(885.4\pm0.9_{\text{stat.}}\pm0.4_{\text{syst.}})$ has the accuracy which is at least 3 times better than the accuracy of other contributing experiments. So the present world mean value of the neutron lifetime is mainly determined by the result of only one experiment, therefore the new experimental measurements are important.

2. Experimental set-up

The measurements were carried out on the high flux reactor at ILL in Grenoble, France (the PF2/MAM instrument); the experimental set-up is sketched in Fig. 1. It is the gravitational trap for UCN and at the same time it can be used as a differential gravitational spectrometer. Therefore
the distinguishing feature of the given experiment is the possibility to measure the UCN energy spectrum after its storage in the trap.

The UCN storage trap is placed inside the cryostat vacuum vessel. The trap has a window and can be rotated around a horizontal axis so that UCN are locked up in the trap by the force of gravity when the trap window is in its upper position.

UCNs fill the trap via the neutron guide, the opened UCN inlet valve and the distribution flap valve (FILLING position, as shown in Fig. 1). Filling takes place when the trap window is in the downward position. After the trap is filled it is rotated into the upper position.

The system maintained the separate "clean" and "dirty" vacuum vessels. Residual vacuum inside the cryostat vacuum vessel was 10⁻⁶ mbar. Such vacuum has small effect on the UCN storage time in the trap. To cool the trap we organised the heat exchange between the trap and the cryostat tank. To do this the helium gas flow through the cryostat vacuum vessel was used and then it was removed to carry out the neutron lifetime measurements.

The height of the trap window relative to the trap bottom defines the maximum energy of UCN which could be captured into the trap. Different window heights will correspond to different cut-off of the UCN energy spectrum. Otherwise, such rotatable trap is a gravitational spectrometer. The spectral dependence of losses can be measured by turning the trap window downward in steps. The trap was kept in each intermediate position long enough to detect most of the UCN in the corresponding energy range. The same procedure allows to simultaneously measure the spectrum of the trapped UCN.

The trap itself is an interchangeable element. In the first phase of the experiment we employed a quasi spherical trap consisting of a cylinder about 84 cm in diameter and 26 cm wide, capped by two truncated cones each 22 cm high, with small diameters of 42 cm. We also used a 76 cm diameter cylindrical trap that was 14 cm long between its end faces. The latter has raised the neutron collision rate with the walls of the trap by a factor of about 2.5 and gives the possibility for the method
of size extrapolation. The narrow cylindrical trap is shown in Fig. 1 by a dotted line.

Fig. 1. The scheme of “Gravitrap”, the gravitational UCN storage system. 1: neutron guide from UCN turbine; 2: UCN inlet valve; 3: beam distribution flap valve; 4: connection unit; 5: “dirty” vacuum volume; 6: “clean” vacuum volume; 7: cooling coils; 8: UCN storage trap (the narrow cylindrical trap is shown by a dotted line); 9: cryostat; 10: mechanics for trap rotation; 11: stepping motor; 12: UCN detector; 13: detector shielding; 14: evaporator
The typical count rate diagram during the UCN storage cycle is shown in Fig. 2. First the trap is filled with UCN in the downward position of the hole. Then the trap is rotated to the monitoring position where the height of the trap window is 10 cm less than at the holding position with the hole upward. This process can be observed by means of the detector through the slits in the distributive valve. When the trap reaches the monitor height the distributive valve changes the position. The trap stays in the monitoring position for 300 s. During this procedure the neutrons whose energy exceeds the gravitational barrier of the trap leave the trap.

Fig. 2. Time diagrams of the storage cycle for two different holding times
Then the trap is rotated to the holding position. All above mentioned procedures are carried out during the time interval 0–700 s, the counting rate is shown in the logarithmic scale on the left side, the counting rate for the subsequent procedures (700–3000 s) is shown in the normal scale on the right side in order to provide more details. After a short (top part of Fig. 2) or long (bottom part of Fig. 2) holding time the trap is rotated to five successive trap positions and is delayed in each position for 100–150 s in order to count UCN. The neutrons counted after each rotation have different average energy. When the UCN trap is empty the background measurement is started. The angle positions of trap are: \( \theta = 30^\circ \) (monitoring position), \( \theta = 40^\circ \), \( E_{UCN} = 58 \text{ cm} \); \( \theta = 50^\circ \), \( E_{UCN} = 52 \text{ cm} \); \( \theta = 60^\circ \), \( E_{UCN} = 46 \text{ cm} \); \( \theta = 75^\circ \), \( E_{UCN} = 39 \text{ cm} \); \( \theta = 180^\circ \), \( E_{UCN} = 25 \text{ cm} \). The angles have to be chosen so as to obtain the similar counts for each portion of UCN (unfortunately, the third portion of UCN in the time diagram in Fig. 2 was not successfully optimised).

3. Methods of the neutron lifetime extrapolation

3.1 Basic relationships

Any neutron lifetime measurement using UCN storage method is based on a rather simple equation (1). The total probability of UCN losses \( \tau_{st}^{-1} \) is broken up into two parts: the first part is the probability of neutron beta-decay \( \tau_n^{-1} \) and the second one is the probability of other possible UCN losses \( \tau_{loss}^{-1} \):

\[
\tau_{st}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1} .
\] (1)

The UCN storage time \( \tau_{st} \) is calculated from the measurements of the number of neutrons remaining in the trap after different holding times:

\[
\tau_{st} = \frac{(t_2 - t_1)}{ln(N_1/N_2)} ,
\] (2)
where $N_1$ and $N_2$ are the numbers of neutrons remaining in the trap after holding times $t_1$ and $t_2$ respectively. There is no need to know the efficiency of the UCN detector, the UCN loss rate during its transport to the detector, etc., since the equation (2) uses only the ratio of $N$.

If the UCN are held in the trap material then $\tau_{\text{loss}}^{-1}$ contains mainly the probability of losses at the trap walls:

$$
\tau_{\text{loss}}^{-1} = \mu(T, E) \cdot \nu(E),
$$

where $\mu(T, E)$ is the UCN loss factor per one reflection, which depends on the UCN energy and the temperature of walls $T$, and $\nu$ is the UCN collision frequency, which depends on the UCN energy and the size of the trap. The UCN loss factor for one reflection can be presented in the following well known form [4], which was derived from an assumption that the reflection of UCN is happened from the potential step with real ($U_0$) and imaginary ($W$) parts:

$$
\mu(y) = \frac{2\eta}{y^2} \cdot (\arcsin y - y\sqrt{1 - y^2}) = \eta \cdot \begin{cases} 
\pi, & y \to 1 \\
\frac{4}{3}, & y \ll 1 
\end{cases},
$$

where $\eta$ is the ratio of imaginary and real parts of potential or scattering amplitude:

$$
\eta = \frac{W}{V} = \frac{b'}{b}, \quad y = \sqrt{\frac{E}{U_0}}.
$$

The UCN loss factor in formula (4) is averaged over the angles of incidence. The imaginary part of scattering amplitude can be presented according to the optical theorem in the following form [4]:

$$
b' = \frac{\sigma_{\text{abs}} + \sigma_{\text{spec}}(T)}{2\lambda}. 
$$

The absorption cross sections are proportional to the
neutron wavelength ($\lambda$), therefore $b'$ and $\eta$ do not depend from $\lambda$ or neutron energy $E$. But $\eta$ is the function of the temperature ($\eta = \eta(T)$) because of the temperature dependence of upscattering cross section ($\sigma_{\text{upscat}}(T)$).

We can rewrite the equation (3) in a different form to combine together both the energy dependencies of the loss factor and the collision frequency, and to extract the temperature dependence of the loss factor:

$$\tau_{\text{loss}}^{-1} = \eta(T) \cdot \gamma(E),$$

where $\eta(T)$ can be defined as the energy independent loss factor, $\gamma(E)$ can be defined as effective frequency of collision which depends on the UCN energy and the trap size. The neutron lifetime value can be obtained by linear extrapolation of $\tau_{\text{st}}^{-1}$ to zero value of $\gamma$. Different values of the UCN effective collision frequency $\gamma$ could be obtained using traps of different size and different UCN energy. The UCN loss factor $\eta$ is the slope of the extrapolation line. The UCN effective collision frequency $\gamma$ can be calculated.

### 3.2 Method of energy extrapolation

To calculate the energy dependence of UCN losses $\tau_{\text{loss}}^{-1}$ we used the numerical and Monte Carlo methods taking into account the motion of UCN in the gravitational field. The simple relation: $\tau_{\text{loss}}^{-1} = \mu(E) \cdot \nu(E)$ was used to calculate the probability of losses. The frequency of collisions $\nu(E)$ with the element of surface $dS$ can be presented as the flux directed to the surface $\frac{1}{4} \nu \rho(v) dS$, where $\rho(v)$ is the UCN density dependent on the UCN velocity. In the gravitational
field the distribution of UCN density is proportional to $\sqrt{E \cdot mgh \over E}$, where $E$ is the UCN energy at the bottom of the trap, $h$ is the height from the bottom. This equation has to be integrated and normalised as UCN have different kinetic energies at different heights from the bottom of the trap:

$$
\tau_{loss}^{-1}(E) = \frac{\int_{0}^{E} \mu(E - mgh) \cdot v(E - mgh) \cdot \rho(E - mgh) dS(h)}{\int_{0}^{E} 4 \rho(E - mgh) dV(h)}.
$$

For comparison with experimental data we have to integrate equation (6) inside the energy interval for each measurement and to take into account the real spectral distribution of UCN density in the trap. The UCN spectrum in the trap was measured just after the monitoring process by means of the procedure shown in the top part of Fig. 2. The modification of spectrum in the process of UCN storage in the trap was taken into account as the small correction to the calculated $\gamma$ function. The additional corrections of the calculated $\gamma$ function were introduced in connection with incomplete emptying of UCN from each energy interval as it can be seen in Fig. 2.

Using the calculated value of losses for different energy as $\tau_{loss}^{-1} = \eta(T) \cdot \gamma(E)$ we can extrapolate experimental data to the neutron lifetime. The result of extrapolation depends on the function $\mu(E)$, which can be a little bit different in reality, for example $\mu'(E)$. To reduce the systematic effect that could arise due to energy dependence $\mu'(E)$ we have to consider the way how to exclude the energy dependence from extrapolation.
3.3 Method of size extrapolation

To exclude the energy dependence $\mu'(E)$ we can do extrapolation to zero losses using the data with the same energy for the traps with different sizes. Using equations for storage time $\tau_1$ and $\tau_2$ for two traps:

$$\tau_1^{-1}(E) = \tau_n^{-1} + \eta\gamma_1(E),$$

$$\tau_2^{-1}(E) = \tau_n^{-1} + \eta\gamma_2(E),$$

we can obtain:

$$\tau_n^{-1} = \tau_1^{-1}(E) - \left(\tau_2^{-1}(E) - \tau_1^{-1}(E)\right)\left[\gamma_2(E)/\gamma_1(E) - 1\right]$$

In this case we can exclude the effect of energy dependence $\mu'(E)$ almost completely, because the final result for the neutron lifetime depends on the ratio $\gamma_2(E)/\gamma_1(E)$. It is easy to show that in the case without gravity using equations (7) and (8) for two different traps and for the defined energy there is a possibility to exclude the $\mu'(E)$ function completely. In real case with gravity a complete excluding of the $\mu'(E)$ dependence is impossible because of the integral equation (6). But the remained effect of influence of the $\mu'(E)$ dependence for the neutron lifetime is negligibly small in comparison with the statistical accuracy of the measurements.

The method of the size extrapolation based on the two traps allows to suppress considerably systematic errors connected with uncertainties of our knowledge about $\mu'(E)$.

4. The low-temperature fomblin coating of traps

We used a new type of the wall coating, the low-temperature fomblin (LTF) that can be evaporated onto the surface in vacuum. This perfluorinated oil has a composition containing only $C$, $O$ and $F$. and
thus a low neutron capture cross section. Previously we had investigated [5] several types of LTF and found that quasi-elastic UCN scattering and thermal inelastic scattering are significantly lower at T<-120ºC than for ordinary Fomblin oil at a near-room temperature. The quasi-elastic UCN scattering is suppressed completely below –120ºC [5] and the expected UCN loss coefficient $\eta$ due to upsckattering is about $2\cdot10^{-6}$ [6].

The new type of LTF used in our experiment has a molecular weight $M = 2354$ and a vapour pressure $P = 1.5\cdot10^{-3}$ mbar at the room temperature. For preparation of the trap coating this oil was delivered to evaporator by means of a vertical tube and some pressure of $He$ in this tube. A spherical evaporator with small holes was heated up to +140ºC by means of an electric heater, and then 3 cm$^3$ of oil were ejected onto the interior trap walls at the temperature of –150ºC. The moving of evaporator in vertical and horizontal directions during deposition was done for uniformity of the coating.

For a preliminary test of oil film quality we used a titanium-coated $Cu$ trap. The trap was a cylinder with diameter of 76 cm and widths of 50 cm. Titanium have the negative scattering length and UCN can not be held in this trap.

The stable storage time $\tau_s = 867 \pm 2$ s was reached after several LTF evaporations (total thickness of 15 µ) at the wall temperature of (–140ºC)÷(–150ºC), warming the trap up to the room temperature and cooling it down to –160ºC. Due to this procedure, the oil at the room temperature filled all the gaps and cracks of the wall and formed a perfect surface. The LTF have been additionally degassed in thin layer at the room temperature. The stability of the coating was investigated for 8 days and no significant change of storage time was observed. Further evaporation did not change the storage time.

For the final measurements we used $Be$-coated traps (quasi-spherical and narrow cylindrical). Since $Be$ is a good UCN reflector we can use even lower temperatures as a possible development of micro-cracks in the coating is less detrimental to the storage time. Using the
$Be$-coated trap we studied the temperature dependence of the storage time for the quasi-spherical trap with an LTF coating (Fig. 3a). The LTF was deposited at −140°C, then the trap was slowly warmed up to −50°C and finally cooled again to −160°C. In this way we covered layer defects by the oil when it was sufficiently liquid. Following the temperature cycle we obtained a higher storage time (872 ± 1.5) s than immediately after evaporation (850 ± 1.8) s. Taking into account the different sizes of the $Ti$ and $Be$ traps we find no difference in the reflection loss coefficient $\eta$ for the two kinds of sublayer.

Fig. 3. a) Temperature dependence of UCN storage time during cooling and warming; b) Temperature dependence of integral count during 1000 s of holding time
This indicates that reproducible oil films were obtained independently of the substrate material.

In the course of these studies with Be trap the quasi-elastic scattering on the liquid LTF was measured. Fig. 3b shows the background of UCN leaving the trap during 1000 s holding time in the upright trap position. During this time we observed an excessive count-rate falling exponentially with the UCN storage time in the trap. This additional background is due to UCN suffering a small energy transfer in quasi-elastic scattering from the liquid wall. These neutrons escape from the trap and produce background in detector counting rate. The process disappears at the temperature below ~ –120°C. This is in qualitative agreement with the measurement of quasi-elastic UCN scattering on this oil in our previous work [5]. Quasi-elastic scattering is seen to be insignificant for T < –120°C. We used in our measurements the temperature of –160°C to be sure that quasi-elastic scattering would not affect our measurements. Using a lower temperature was undesirable because of the possible cracks in the coating that loses its plastic properties at this temperature.

The stability and identity of coating for different traps is the most important question for correctness of the size extrapolation method to the neutron lifetime. Therefore the correspondence of the properties of LTF coatings was verified many times in the course of measurements. Fig. 4 shows eight storage time results for the quasi-spherical trap and seven storage time results for the narrow trap. The measurements have been carried out after new evaporations, warming and cooling, new evaporations and so on. At last vacuum conditions were improved from 5·10^{-6} mbar up to 3·10^{-7} mbar due to installation of a LHe cryopump near the storage volume. The storage time in the course of the experiment has been reproduced with the accuracy of about 1 s for the wide trap and with a little bit poorer accuracy for the narrow trap.

Therefore we have no reason to consider the different loss factor $\eta$ for the different traps.
Fig. 4. Demonstration of stability of the LTF coating during the measurements. UCN storage times for wide and narrow traps plotted versus run number
5. Results of measurements and extrapolation to the neutron lifetime

The results of measurements of UCN storage time for different energy intervals and for different traps (wide and narrow) are presented in Fig. 5 as a function of effective frequency of collisions $\gamma$. 

Fig. 5. Result of extrapolation to the neutron lifetime using joint energy and the size extrapolation method. Measurements made with a spherical (open circles) and cylindrical (filled circles)
The extrapolation of all data to the neutron lifetime gives a result of $877.60 \pm 0.65$ s with $\chi^2$ value of 0.95. It means that joint extrapolation is possible and there is no large difference between the energy extrapolation method and the size extrapolation method. Nevertheless we can do the energy extrapolation for each trap and combining both results we obtain $875.55 \pm 1.6$ s.

Fig. 6. Extrapolated values for the neutron lifetime for different average UCN energies using the size extrapolation method. The solid line corresponds to the final neutron lifetime fit.
For the size extrapolation method we have to connect two points for different traps and for the same energy interval, and then to calculate the average value of all results of extrapolation to the neutron lifetime. Fig. 6 shows the results of the size extrapolation to the neutron lifetime for the different energy interval and the average value of the size extrapolation method: $878.07 \pm 0.73$ s.

The obtained results are in reasonable agreement. The loss factor $\eta = 2 \cdot 10^{-6}$ obtained in this experiment is in agreement with transmission experiment [6]. As a final result for the neutron lifetime we prefer to use the result of the size extrapolation which has a rather weak dependence on $\mu(E)$ and we take it as the most reliable.

6. Monte Carlo simulation of the experiment and systematic errors

The method of the size extrapolation using the calculated $\gamma$-function requires the estimation of its accuracy. To do the estimation of accuracy and to be sure in reliability of the used method we developed Monte Carlo (MC) simulation of the experiment.

In the MC-simulation the behaviour of neutrons was described taking into account the gravity field, the form of the storage traps, geometry of the secondary vessel and UCN guide for transportation of UCNs to detector. As a result we have a possibility to simulate the process of measurements and to obtain the time diagram like it is shown in Fig. 2. The UCN storage time in traps has been calculated the same way as in the experiment, and the extrapolation to the neutron lifetime using the calculated $\gamma$-function was done as well. The single free parameter of this MC-simulation was coefficient of diffusive scattering at the interaction with the trap surface. Knowing the probability of the mirror reflection is very important in case the mirror reflectivity is extremely high, for example 99.9%. In this case a very specific behaviour of UCN inside the trap is possible and the obtained result is very difficult to predict.
Fig. 7. Monte Carlo simulation of the experiment. Modelling the trap emptying process for the narrow cylindrical trap.
The comparison of MC simulation with experimental diagram allows to conclude that the probability of diffuse scattering of UCN on the LTF coating is 10% or more. Fig. 7a shows the comparison of experimental diagram and MC simulation with the probability of diffuse scattering, 10% and 100%, which successfully describes the experiment. In case of the probability of diffuse scattering 0.1% the description of the experiment is not satisfactory. The example of this calculation is shown in a large scale (Fig. 7b) for the first part of the time diagram, which is the most sensitive to the effect of mirror reflections.

The final simulation of the experiment was done for the probability of diffusive reflection 10% and 1% as well. The Fig. 8 shows the simulated storage time extrapolated to the neutron lifetime for the wide cylindrical and the narrow cylindrical traps and for the five different energy intervals of UCN. For the simplification of MC calculations we used for the wide trap the cylindrical form instead of the quasi-spherical one. The data treatment of simulated measurement shows that neutron lifetime which was introduced in simulation was reproduced with the accuracy of ± 0.236 s. This accuracy is the statistical accuracy of MC calculation, no systematic deviations were found. As the systematic uncertainty of the size extrapolation method with calculated γ-function we can use the uncertainty of ± 0.236 s.

7. The influence of the residual gas for UCN storage

On the level of accuracy measurements about 1 s the influence of the residual gas with pressure of 5·10^{-6} mbar is already important. This correction cannot be measured directly by means of improvement of vacuum by one order of magnitude because expected effect is less than the statistic uncertainty. Therefore we reduce the velocity of pumping and increase the residual gas pressure up to 8·10^{-4} mbar. Using this way the (pτ) – parameter was measured for residual gas: (pτ) = 9.5 mbar·s. Thus the calculated correction for storage time is (0.4 ± 0.02) s and it does not depend on UCN energy. Therefore this correction can be used as the correction for the neutron lifetime result.
Fig. 8. Monte Carlo simulation of the experiment. Modelling the extrapolation to n-lifetime
● – wide trap, probability of diffusion reflection 10%;
○ – wide trap, probability of diffusion reflection 1%;
▲ – narrow trap, probability of diffusion reflection 10%;
▼ – narrow trap, probability of diffusion reflection 1%
8. Final result for the neutron lifetime and the list of systematic corrections and uncertainties

The table shows the values of systematic effects with their uncertainties. The main contribution to uncertainty we have due to the statistics of measurements. The next one is the uncertainty of calculation of $\gamma$ – function. The contributions due to influence of $\mu(E)$ -function shape and uncertainty of UCN spectrum are considerably less. They were estimated by means of variation of their parameters in frame of uncertainty allowed by the experimental data. Thus the total systematic correction is $(0.4 \pm 0.3) \text{ s}$ and the final result for the neutron lifetime from our experiment is $(878.5 \pm 0.7_{\text{stat.}} \pm 0.3_{\text{syst.}}) \text{ s}$.

Table. The systematic effects and their uncertainties

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<td><strong>Total systematic effect</strong></td>
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<td><strong>0.3</strong></td>
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9. Conclusion

In the presented experiment the storage time is the closest to the neutron lifetime. The difference between the best experimental storage time and the neutron lifetime is about 5s only. It gives the confidence in the reliability of the obtained result.

The new result for the neutron lifetime can be used for the unitarity test of Cabibbo-Kobayashi-Maskawa (CKM) matrix. The Fig. 9 shows $V_{ud}$ versus $G_A/G_V$ plot from work [3] with new result for the neutron lifetime.

The new lifetime result is different from the world average value by 6 standard deviations, and by 4 standard deviations from the previous most precise result [1]. However, the new result for the neutron lifetime together with $\beta$ – asymmetry in neutron decay ($A_0 = -0.1189(7)$ [2]) is in a good agreement with the Standard Model.

10. Acknowledgements

The authors are grateful to:

- V.Alfimenkov, V.Lushchikov, A.Strelkov and V.Shvetsov for their contribution at the initial stage of the development of the installation;
- A.Steyerl, O.Kwon, N.Achiwa for participation in measurements and fruitful discussions;
- T.Brenner for the intensive and very helpful assistance during the experiment;
- PSI for the help in manufacturing of UCN traps;
- Russian Foundation of Basic Research for support under contract 02-02-17120;
- Russian Academy of Sciences for to the program “Physics of elementary particles”.
Fig. 9. $|V_{ud}|$ versus $G_A/G_V$. $|V_{ud}|$ was derived from higher quark generation decays via $|V_{ud}| = \sqrt{1 - |V_{ud}|^2 - |V_{ub}|^2}$ predicted from unitarity, from Ft values of nuclear-decays, and neutron β-decay.
References


Работа поступила в Издательство ПИЯФ РАН 11.05.2004 г.