PROGRAM OF RESEARCH INTO FUNDAMENTAL INTERACTIONS BY PIK REACTOR – PART III: MEASUREMENT OF NEUTRON LIFE TIME

A.P. Serebrov[1], A.V. Vasiliev[1], V.E. Varlamov[1], P. Geltenbort[2], K.A. Gridnev[3],
E.A. Kolomensky[1], I.A. Krasnoschekova[1], M.S. Lasakov[1], D.V. Prudnikov[1], A.K. Fomin[1],
A.V. Fomichev[3], O. Zimmer[2], I.V. Shoka[1]

[1]B.P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina, Russia
[2]Institut Laue – Langevin , Grenoble, France
[3]St. Petersburg State University, St Petersburg, Russia

The research program on fundamental interactions with ultra cold and polarized cold neutrons on GEK-4-4' channel of PIK reactor is presented. An experimental complex scheme comprises: a source of cold neutrons in deuterium reflector of the reactor, a source of ultra cold neutrons (UCN) on superfluid He on the output beam of cold neutrons of GEK-4 channel and a number of experimental installations on neutron beams. Using a UCN beam, we are planning to make an experiment on a neutron lifetime measurement with a big gravitation trap. The article discusses the state of things relevant to preparation of experimental set-up as well as the current situation in this field and motivation for neutron life time measurement.

Key words: ultra cold neutrons, neutron lifetime

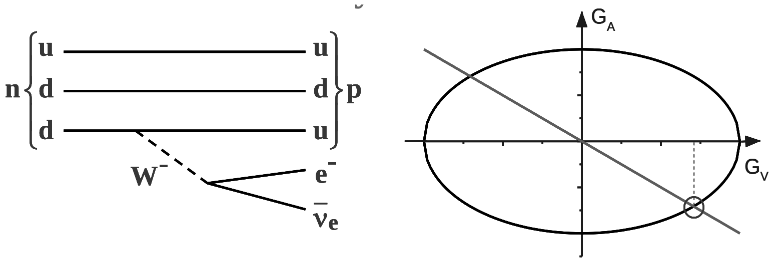
As most elementary particles, neutrons consist of quarks. Different combinations of quarks provide diversity of elementary particles. Quarks in elementary particles are in a confinement state, they cannot escape elementary particles, but they can mix with each other producing different versions of elementary particles decays. In Standard Model (SM) of elementary particles, mixing of quarks is described by the Cabibo-Kobayashi-Maskava matrix (CKM) (Fig. 1), which must be unitary, which provides evidence for our entire conception concerning the number of generations of quarks and leptons. Values of the matrix elements are identified from weak decays of elementary particles. In particular, a neutron decay is determined by transition of d-quark into u-quark or by a matrix element V_{ud}. Knowledge of the exact value of V_{ud} plays a great role for testing unitarity of CKM matrix, as V_{ud} element is the biggest one. V_{ud} element can be identified from β-decay of nuclei and from β-decay of a neutron. Identification of V_{ud} from β-decay of a neutron is more suitable from the point of view of theoretical simplicity of describing the process compared to a decay of nuclei. For identification of V_{ud} from β-decay of a neutron, it is necessary to measure the neutron lifetime

---

[1] Serebrov Anatoliy Pavlovich
Russia, 188300, Leningrad district, Gatchina, Orlova Roscha, PNPI
Тел.: +7 81371 46001
Факс: +7 81371 30072
E-mail: serebrov@pnpi.spb.ru

and β-decay asymmetry with high precision. Accuracy for theoretical calculations of the radiation corrections to determine V_{ud} with 0.05% precision; hence, accuracy of the neutron lifetime measurement should be as high as that. Accuracy of 0.1% in measuring the neutron lifetime has been attained in the experiment with ultra cold neutrons being stored in traps.

Precision measurements of the neutron lifetime prove to be extremely important for verifying the model of the Universe formation at its early stage. Approximately 100 s later after the Big Bang, at temperature $T > 10^{10}$ K ($E > 1$ MeV), leptons, hadrons and photons were in the state of thermodynamic equilibrium. The rate of reactions, owing to a weak interaction, is determined by the same magnitude as that of neutron decay. Dependent on the rate of weak reactions is the temperature, at which neutrino leaves the process and at which the neutron-proton relation is formed during an early stage of primary nucleosynthesis. In further process, the neutron decay additionally changes the neutron-proton relationship. In the Big Bang model, the observed magnitudes are abundance of deuterium and ^{4}He. These values depend on the ratio of the number of baryons to that of photons (η) at the moment of nucleosynthesis, as well as on the neutron lifetime τ_n. Value η (baryon asymmetry of the Universe) is measured in cosmic investigations of the microwave relict radiation, hence, all the values turn out to be measurable and related to each other. In particular, in the model of primary nucleosynthesis, the neutron lifetime variation by 1% leads to changing ^{4}He abundance by 1.5% (at the fixed value of η) or to a baryon asymmetry variation by 17% (at the fixed value of ^{4}He abundance). Unfortunately, relative precision of measuring ^{4}He abundance is not sufficiently high (± 0.6%), though, measurement precision of baryon asymmetry is improving very rapidly owing to cosmic studies and comprises now ± 5%. Thus, the neutron lifetime should be measured much better than with accuracy of 1%, for it to be successfully used in the model of primary nucleosynthesis.



CKM mixing matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$ft\left(1+\underset{\sim 1.5\ \%}{\Delta_R}\right)\left(1+\underset{\sim 2.4\ \%}{\delta_R}\right) = \frac{k}{|V_{ud}|^2 G_F^2 \left(1+3\lambda^2\right)}$$

$$\lambda = \frac{G_A}{G_V} \qquad A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

$$G_V = G_F \cdot V_{ud}$$

$$\boxed{|V_{ud}|^2 = \frac{4908.7 \pm 1.9\ \mathrm{s}}{\tau_n\left(1+3\lambda^2\right)}}$$

W.Marciano
A.Sirlin
PRL 96, 032002
(2006)

Fig. 1. Determination of matrix element V_{ud} from β-decay of neutron.

As an example, one can quote the result obtained in 2004 at PNPI NRC KI, on the installation created in collaboration with JINR. A new result on the neutron lifetime, measured with a record accuracy ($\tau_n = 878.5 \pm 0.7_{stat.} \pm 0.3_{sys.}$ s) on the UCN beam of the reactor ILL, proved to be quite unexpected. The obtained neutron lifetime was by 7.2 s less than the world average value and by 6.9 s less than the latest most accurate result. This difference is far beyond the limits of errors and comprises 6.5 and 5.6 of standard deviation, correspondingly [1,2].

A new result proved to be very important both for the physics of elementary particles and for astrophysics and cosmology. It has eliminated the existed disagreement between experimental data and SM of electric weak interactions.

At present, a new more precise experiment for measuring the neutron lifetime in a material trap has been elaborated. The installation makes use of the principle of a gravitational valve for holding UCN in a material trap. The UCN storage volume in a new trap is approximately 4 times larger than that in a previous one, in addition to this, a new installation will employ an insert, which will be lifted and lowered into a trap without opening the installation. It enables both to eliminate systematic errors and to considerably increase statistical accuracy of the experiment. It is expected that precision of measurements with this setup is to be 0.2 s. Increase of precision will make it possible to resolve the arising disagreement between different approaches to neutron lifetime measurements – the beam technique and that of UCN storage. The difference between these two techniques is that in a beam experiment, one measures only one mode of a neutron decay with a proton emission, while in storing UCN, one measures all possible channels resulting to disappearance of a neutron. At present, the neutron lifetime measured in storing UCN is approximately by 4 standard errors less [3], than that measured in a beam experiment. Though, the most probable explanation of it would be a systematic error in a beam experiment, however, one cannot exclude presence of some additional unknown mode of a neutron decay.

Fig. 2 presents a scheme of a new installation [4] at the assembling stage on the reactor ILL (Fig. 3).

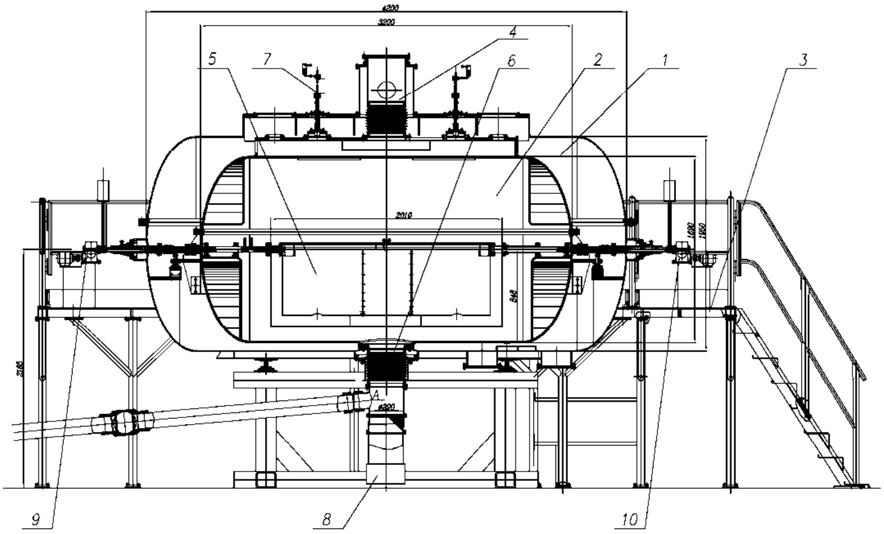


Fig. 2. A scheme of a big gravitational trap: 1 – an external vacuum vessel; 2 – an internal vacuum vessel; 3 – a service platform; 4 – an input for pumping out an internal vessel; 5 – a trap with an insert in low position; 6 – a neutronguide system; 7 – a system for sputtering of the trap and insertion; 8 – a detector; 9 – a trap rotary gear; 10 – a rotary gear for an insert.

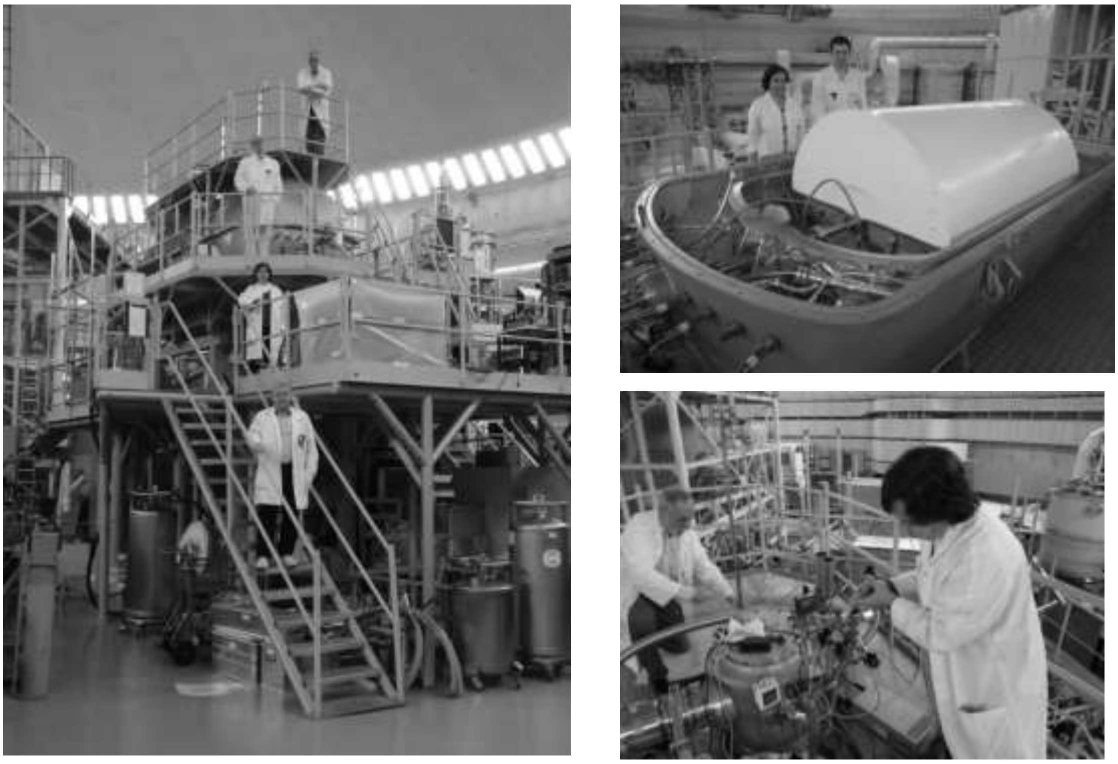


Fig. 3. A final stage of assembling a big gravitational trap.

A new installation with a big gravitational trap presents further development of methods and approaches applied in a previous experiment. We are planning to attain accuracy of measurements of 0.2 s, which is 4 times better than the existing level of accuracy. After the measurements at ILL have been carried out, this installation is to be moved to the PIK reactor, where the UCN density is expected to be 100 times higher.

At present, a few experiments are planned in the world on the neutron lifetime measurement and study of neutron decay asymmetry, therefore, the PNPI program for the PIK reactor is in mainstream of advancement of the direction of physics.

Acknowledgements

We are grateful to workers of the PNPI experimental equipment workshop headed by E.P. Volkov for their assistance in preparation of experimental apparatus and also to the personnel of the WWR-M and ILL reactor for their help in assembling and maintenance of the installations. The presented research is conducted at the support of the administration of two institutes: PNPI and ILL, which is extremely important for carrying out current investigations and implementing the plans scheduled for the PIK reactor.

Different parts of the research performed were carried on in PNPI NRC «Kurchatov Institute», supported by the Russian Foundation for Basic Research (grant no. 13-02-00570-a) and Russian Scientific Foundation (grant no. 14-22-00105) in full correspondence with independent plans for these projects.

References

1. *Serebrov A.P., Varlamov V.E., Kharitonov A.G.* et al. Measurement of the neutron lifetime using a gravitational trap and a low-temperature Fomblin coating // Physics Letters B. 2005. V. 605. P. 72.
2. *Serebrov A.P., Varlamov V.E., Kharitonov A.G.* et al. Neutron lifetime measurements using gravitationally trapped ultracold neutrons // Physical Review C. 2008. V. 78. P. 035505.
3. *Yue A.T., Dewey M.S., Gilliam D.M.* et al. Improved Determination of the Neutron Lifetime // Phys. Rev. Lett. 2013. V. 111. P. 222501.
4. *Serebrov A.P., Fomin A.K., Kharitonov A.G.* et al. New installation for measurement of neutron lifetime with a big gravitational trap of ultracold neutrons // JTP. 2013. V. 83. P. 136