STUDIES WITH ULTRA-COLD AND COLD NEUTRONS

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EDM-experiment

The experimental search for neutron electric dipole moment (EDM-experiment) is considered to be one of the crucial experiments in physics as it should explain the nature of violation in relation to time reversal. In practically every work concerning T-violation, possible effects are estimated basing on normalization to the upper limit of neutron EDM. So far it has been the most sensitive method for experimental progress in the T-violation problem. More than a half of 50-year EDM-experiment history is described by ultra-cold neutron methodology. A considerable contribution to this problem has been made at PNPI. Here the EDM neutron limit was reduced from $3 \cdot 10^{-24} \text{ e\,cm}$ down to $1 \cdot 10^{-25} \text{ e\,cm}$ (see Fig. 1), which allowed to reject a number of theoretical ideas about the nature of T-violation.

Prior to reach a new neutron EDM limit a lot of efforts were put into creation and modernization of EDM-spectrometer, and also a great work was done to understand how to handle ultra-cold neutrons. Feasibility to solve such a principally significant problem resulted in formation of new neutron handling techniques. A great number of various physical questions, concerning interaction of UCN with substance, aroused. All this gave birth to a new direction named ultra-cold neutron physics.

The first requirement was a sufficiently high intensity of ultra-cold neutron beams. Huge efforts were spent to solve this problem. And now a lot of attempts are still made to increase the efficiency of UCN sources and to find new approaches. The Fig. 2 shows UCN density increase and achievements of different laboratories of the world. For the years that passed since the first experiments, the UCN density has been increased by 7 orders of magnitude. The role of PNPI in UCN source development is very significant. For a decade, starting from the middle of 70-s, the maximum UCN density belonged to Gatchina. And only when the UCN source based on a liquid deuterium moderator and Steyerl’s turbine was launched in Grenoble, the UCN density in Gatchina became by 5 times less due to difference in initial fluxes of thermal neutrons on the sources.
All mentioned above relates to a 30-year period in development of the EDM-experiment at PNPI, and is, undoubtedly, worth a closer look. Various stages of the experiment development and the most memorable events and circumstances, that gave deep impressions and made the lives of its participants emotionally brighter, are presented further on in this article. First of all, I would like to introduce the main authors of this experimental age at PNPI, as their contributions make up the major part of this work.

Neutron EDM measurements with ultra-cold neutrons were started by V.M. Lobashev and his team consisting of L.A. Savostin, G.D. Porsev, A.P. Serebrov, A.I. Egorov, V.A. Nazarenko. Later on V.F. Ezhov and S.N. Ivanov naturally joined the creative process and took active part in the works of this versatile task. V.F. Ezhov contributed most to the high-voltage problem, and S.N. Ivanov – to the problem of stabilization of magnetic field. The next to join the EDM studies were R.R. Taldaev and then I.S. Altarev and Yu.V. Borisov. Each of them found his place in the team. I.S. Altarev played a great role in the development of liquid hydrogen UCN sources, R.R. Taldaev – in the development of preparation techniques of various coatings for neutron guides and UCN traps, Yu.V. Borisov – in the development of electronic equipment for the experiment, and magnetic field stabilization systems. Finally, A.A. Brandin displayed his professional skills at the stage of realization of the storage type EDM-spectrometer, and Yu.V. Sobolev – in setup modeling, data processing and analysis of results. As a whole, the EDM-experiment gave rise to a generation of physicists, who now are successfully involved in other experiments. The main results of the EDM-experiment are presented in the works [1−13]. This article illustrates that part of experimental activity which, as a rule, stays out of official publications.

The first experiments with UCN [1]

So, everything started with the design and manufacturing of the vertical channel and the EDM spectrometer, which had taken about 2 years. It must have been the most quiet time comparing to what was going to come. In parallel with design works we managed to understand the theory of UCN production, and to develop UCN source calculation methods, which turned to be very useful later on. The first experiments with UCN started in 1972 at the reactor horizontal channel in order to master UCN handling methods. The vertical channel was planned to serve as an intensive UCN source and to provide necessary conditions for neutron EDM measurements. The horizontal neutron guide with an aluminum converter allowed to obtain a UCN flux of 5 n/s, which at that time was a progress. However the flux was less than expected and required for the EDM-experiment. At this point it became clear that the problem of UCN extraction from the reactor spectrum needed a thorough approach.

As soon as the first ultra-cold neutrons were obtained, an attempt to verify the possibility of their storage was made. The experiment was simple – a tube, two shutters and a UCN detector. Initially it was not even automated. Shutter management was manual, which gave an impression that we literally held neutrons by hands. However, it turned out that the ability of UCN to be stored in the trap was much less than calculations had predicted. In our experiment the UCN trap storage time was 15 seconds. Only later, 25 years after that, it would be possible to obtain a storage time (to be more exact, a storage time determined only by losses in walls) of about 8 hours, that is, by 2000 times better, only later the intensity value would be $5 \cdot 10^5$ n/s, but at that time it was only 5 n/s – discouragingly low. Moreover, it was noticed that UCN flux reduced due to degradation of neutron guide properties under radiation conditions. Since then it would remain a persisting problem for years to come and, unfortunately, still no solution has been found.
The start was not too enthusiastic. As it often happens, first experiments reveal how complicated the problem is and how far from its understanding you are. Further on, difficulties are overcome, but very slowly, step by step, and with great efforts.

Low UCN storage time (several tens of seconds) did not allow to measure neutron lifetime, however it was quite sufficient for the EDM-experiment. But the more important requirements for the EDM-experiment were polarized neutrons and their high intensity. It was our first attempt to polarize UCN.

For UCN polarization and its analysis thin ferromagnetic films made of isotopic iron ($^{54}$Fe) were used in order to neutralize magnetic and nuclear barriers in the best possible way. Isotope cost was of no concern at that time. The most difficult task was to realize a UCN spin-flip. Due to a low UCN velocity its spin adiabatically follows the direction of magnetic fields, and therefore UCN spin-flip is a very hard task. Besides, for example, in a well-known spin-flip method, foil with current, a UCN beam gets weakened in the foil. We decided to use an alternative magnetic field with resonance frequency and high amplitude in order to depolarize a UCN beam passing through a neutron guide. Thus it was possible, may be not in such a perfect way, to measure UCN polarization. How surprised we were when polarization value exceeded 100%. It took some time to find an explanation. V.I. Lustchikov, our colleague from Dubna, produced an idea that a spin-flip could occur if there was a magnetic field gradient within the range of resonance. We developed and verified the idea. It turned out that the magnetic field gradient was produced by an adjacent installation. Thus, by a lucky coincidence, an adiabatic resonance flipper was experimentally invented. It is rare that nature gives something out so easily.

Later on this spin-flip method was used for cold and thermal neutrons. At present a great number of polarized neutron beams is equipped with the adiabatic resonance flipper, including the PF1 beam at ILL (Grenoble) and at PSI (Switzerland). Subsequently this idea logically developed into the adiabatic method of separate oscillating fields.

In the same experiments at the horizontal channel №7 various types of neutron guides were studied: electro-polished stainless tubes, glass tubes with internal Ni coating, neutron guides made of polished stainless plates of 12th purity class and of glass plates of 14th purity class with $^{58}$Ni isotope coating. A new method for electro-polishing of a tube internal surface was developed and even copyrights – registered. In general it was quite an enthusiastic activity, which, however, resulted in a pair of acid burnt trousers. Nowadays the tube polishing is done at the PNPI workshop by an anode-mechanical method. And, of course, the surface quality is incomparably higher, almost 13th class. The results of those experiments with various neutron guide types confirmed the correctness of the main decisions of the vertical channel project.

**The first vertical channel for UCN extraction**

The vertical channel was developed with a thorough approach to the neutron guide equipment (14th class of mirror polishing, $^{58}$Ni coating), and installed in the center of the reactor active zone. This place became popular with us after well-known V.M. Lobashev’s experiments, the place with a maximum neutron flux, which has been continuously used by physicists for over 30 years with success for fundamental studies. However, on the other side, it produces some difficulties for reactor maintenance. That is why we try not to miss any opportunity, including this one, to express our thanks to the reactor team and its leaders: K.A. Konoplev and R.G. Pikulik.

The first vertical channel gave a UCN flux of 300 n/s. And even this quite an insignificant result lived only for a few hours. Later it became clear that one of the glass plates of the vertical neutron guide broke and its pieces blocked the surface of a beryllium converter. After this accident we had not produced glass neutron guides for the vertical part of the channel any more. As an alternative solution, polishing methods for stainless steel were developed at the PNPI workshop (I.M. Voronenko, L.G. Malyarenko, L.Sh. Rabinskiy, A.N. Kanaev).

The next vertical channel with the neutron guide made of high-polished stainless steel and with a non-cooled beryllium converter gave a UCN flux of 1200 n/s. That was a sufficient flux to start the works.
The first resonance curve [2]

The magnet-resonance spectrometer with a three-layer magnet screen was manufactured and we were looking forward to observing the thinnest curve of the neutron magnetic resonance. The point was that the time of flight in the beam experiment was $10^{-2}$ seconds and the time of storage of UCN in our setup was about 5 seconds. Consequently the resonance width must have been by 500 times less and must have had the value of $3 \cdot 10^6$ Gauss. It took us a month to discover the resonance. It was really very thin, and the calibration quality of the magnetic field was not enough to locate it. Actually there was another reason preventing us from locating the resonance. It had quite a strange shape due to the fact that one coil was placed not in parallel with another, which resulted in a phase shift and a change in the shape. Besides, due to a wide UCN spectrum the efficiency of the Ramsey method was very low. After that the adiabatic method of oscillating magnetic fields was proposed and realized. This method allowed to work with any neutron spectrum without efficiency loss. As it was mentioned above, this method logically developed from the adiabatic spin-flip method. The new resonance method was quite a significant progress in the task of accuracy improvement.

Cooled beryllium converter [3]

However, the value of UCN intensity was still not sufficient and we felt the need for a better stability of magnetic field. In order to improve the statistical accuracy of the experiment we had to explore cooled UCN sources.

A cooled beryllium UCN source could be a simple, but still quite efficient solution. Fortunately, all calculations had already been done earlier and showed that UCN density could be increased by approximately 10 times. However, there was quite a difficult task of thermo-physics to be solved, it was necessary to have in the reactor zone (where everything can melt in a few minutes, if no powerful flux of cold water is provided) a temperature of 20 K. Therefore under conditions of such heat release it was an extraordinary task for cryogenics. Moreover, it was a hard decision to make, even though we knew there would be 100% guarantee. This task could be successfully realized by minimizing the weight of a heat exchanger and, at the same time, conserving the square of the heat-exchanger surface. That was when we mastered the methods of thermophysical calculations, which turned out to be useful for the following experiments. Three more different cooled sources are presented below.

A unique heat exchanger with a very high ratio of the heat-exchange surface square to its weight was produced by a scientific-production firm named “Gelievaya tekhnika”. There were some difficulties to find the permission for the purchase of a helium refrigerator. But this problem was solved with the help of N.M. Reinov who used his talent to open the doors of authorities. A helium refrigerator “HGU-500/15” with a cooling power of 500 W at the temperature of 15 K was also purchased from this firm. 500 W does not seem to be a large value, however, at this temperature level due to a very low efficiency it requires a 60 kW compressor (and one more as a back-up), a 6 m$^3$ gas-holder, liquid nitrogen tanks and a good deal of other equipment. So after installation of the entire setup it seemed as if a part of the cryogenic department had moved into the reactor hall. As a matter of fact, it really happened, because people from this department were responsible for installation and maintenance of this setup (A.G. Kharitonov, G.V. Varm, P.N. Kirillov, I.I. Sokolov, V.P. Mitin and others). The potential for low-temperature equipment, that we acquired along with the purchase, played a very important role afterwards. The refrigerator setup was used in multiple ways: firstly, in the EDM-experiment, for operation of a liquid hydrogen UCN source in the V13 channel; secondly, in the neutron lifetime experiment, and, lately, for the works with a solid deuterium UCN source.

The UCN source itself required a special-quality beryllium. The most important factors were its chemical purity and homogeneity of density. To get it we had quite an interesting trip to a distant city of Ust-Kamenogorsk, to a restricted-access factory. Now it seems even surprising how enthusiastically people reacted to demands of science at that time. Of course, besides a close contact with immediate performers, an official instruction from above was required. Conventional beryllium prepared by the method of hot pressing was not what we needed. A melted large-crystal sample could have probably satisfied our requirements, however, the best solution was to use a crystal of beryllium. The crystal was grown in the factory laboratory. It had high patchiness, but what we needed most was its homogeneity to provide transparency for UCN. UCN beam experiments proved these samples to be much better than those of conventional extruded beryl
lium. However, melted beryllium can be successfully used for a cooled UCN source just as well as a mono-crystal.

UCN beam intensity in the new channel with a cooled beryllium converter (Fig. 3) reached the value of $3 \times 10^4$ n/s, and the gain factor of UCN yield due to cooling had the value of 12 times.

However, UCN intensity improvement was a solution only to the problem of statistical accuracy. There were still two other problems that required just as much effort – high voltage and stability of magnetic field.

Fig. 3. The scheme of the channel with a cooled UCN source in the active reactor zone:
1 - heat releasing elements; 2 - a lead screen;
3 - a mirror neutron guide; 4 - cryopipes

High voltage for EDM experiment [11]

In the EDM-experiment a voltage of 150-200 kV was required in order to obtain a sufficient value of sensitivity. This voltage had to be applied to the UCN storage chamber made of an isolating material with a high critical velocity of UCN. The voltage value itself called for a respectful and attentive approach. We started from purchasing high-voltage sources, which were sold as part of roentgen and paintwork devices, and finished with manufacturing our own ones. But before we started our own production we also had used high-voltage sources manufactured specially for space research. These sources were very compact as they were designed to be placed on satellites. Unfortunately, they had only one polarity and we had to develop an oil-filled polarity switch.

Movement of oil surface in the switch reservoir caused by polarity reversal made quite a fascinating show. However, it was not as fascinating when one had to merge his arms elbow-deep in oil to fix the unreliable mechanical part of the switch. We physicists could easily put up with this little inconvenience. But there was another principal problem of the experiment. Reversal of high-voltage polarity resulted in a sparkling effect with quite powerful currents, which affected the resonance location due to magnetization of the magnetic screen. It required two actions to be taken: firstly, we needed to isolate the case of the high-voltage system; secondly, we had to design a system that would allow to reverse polarity without the sparkling effect. Such a system was designed and represented as a set of two inter-connected sources with opposite polarities. Of course, in this case only one of them was turned on, and the other one at this moment served as a load resistance. The functions of the sources switched at the polarity reversal. The polarity reversal was done through a low-voltage network without the sparkling effect. Firstly the source of this type was filled with a compound, which caused difficulties for repair works. Then another high-voltage source was manufactured and placed into a tight tank filled with dry nitrogen. For this type of source practically no repair works were required.
Also we faced quite an interesting problem concerning a limiting high-voltage resistor, through which high voltage was supplied to a spectrometer chamber. It was another unreliable element because it accumulated much power in case of a spark inside the chamber. Therefore it was important to distribute this power along a wide area. In other words, we had to create a very long and sufficiently homogeneous high-voltage resistor with a nominal of 100 MΩ.

Someone proposed an extraordinary and daring decision: to extract the thread from the high-voltage cable and to fill the empty space with water, which would function as a load resistor. The most surprising fact was that our mechanical engineers managed to extract the 5-meter thread pressed into a polyethylene cable. Also, what seemed interesting was that heavy water turned out to be more suitable for the task than conventional distilled one. It was, of course, not due to its isotopic effect, but due to its high chemical purity.

Each element of the high-voltage system required thorough design works, but the most important of all were UCN traps, also functioning as isolators between high-voltage electrodes (see Fig. 4). The task was to have the maximum electric field intensity without electric breakdowns and considerable leakage currents, as they could result in a false effect due to co-existing magnetic fields. The first experiments for selection of the most suitable materials and combinations of electrodes and isolators were carried out inside a large bell-glass to provide for visual observation. Fluorescence effects caused by leakage currents revealed weak points and showed us what we had done wrong. Unfortunately, extruded beryllium oxide, which we planned to use for trap walls, under high voltage appeared to be flashing as a neon sign. So we had to use glass cylinders covered with a thin layer of beryllium oxide. Here a number of alternatives was available: beryllium electrodes with glass isolators, then electrodes coated by 58NiMo that has a very high boundary velocity, quartz traps coated with beryllium oxide and beryllium coated electrodes again. We even tried to use plexiglass.
coated by deuterium polyesterene. $^{58}\text{NiMo}$ alloy was specially developed in order to eliminate magnetic properties of Ni.

It had been successfully used as an electrode coating material until storage time reached the value of 90-100 seconds. Only then UCN depolarization processes started to develop slowly, and we had to use beryllium coating again. We had to realize a very difficult technology of coating production from beryllium oxide by a method of high-temperature baking. Then we also realized sputtering of beryllium in the oxygen atmosphere ($10^{-3}$ torr) so that beryllium oxide immediately developed on the can surface. These so-called cans represented quartz cylinders with a diameter of 0.5 m, which were cut out of a whole optical glass piece. Pieces of such size are used for production of illuminators for space ships in order to provide for a wide spectral range up to ultra-violet, and we employed high conductivity homogeneity of this material to obtain the maximum possible voltage.

The voltage value with which it was possible to carry out the works was usually about 120–150 kV. To rise the voltage to the mentioned value we had to carry out quite a delicate procedure – a high-voltage training of the system surface – which required a lot of patience. Any haste would lead to a breakdown, after which it would be necessary to start from the beginning. With time this procedure had been experienced and mastered, and now it has been handed over to a computer.

The first neutron EDM measurements [2]

Unfortunately, there was another problem about high voltage except for obtaining the maximum possible value. It was also very important to detect a false effect arising due to a correlation between high voltage and other systems, for instance, the magnetic field stabilization system. A correlated magnetic field shift of $10^{-9}$ Oe could have been lethal for the experiment. Therefore a differential system of measurements, consisting of two chambers with opposite electric field directions, was realized (see Fig. 4). Thus a high-voltage polarity reversal would cause EDM-effects with different signs, whereas a false effect arising due to a magnetic field change would have the same sign for both chambers.

Further on this measurement system developed into a double-analysis of polarization, which allowed to detect both spin components of a neutron beam using a separate detector for each component (see Fig. 4). As a result, we had a system of correlative measurements working on four detectors. Later on this would be very important for the analysis of measurements, as, on one hand, we could not allow ourselves to discover a false EDM, and on the other, it would be a shame to miss the real one.

The cooled beryllium source, the differential system of measurements, the polarization double-analysis system and the high-voltage system – all was up and running. It was time to start the first EDM measurements.

No EDM was discovered. Of course, no one expected to win so easily. Accuracy advancement amounted to 2 times only. Only later, when Gatchina and Grenoble results would simultaneously show two standard deviation, some excitement, stirred up by competition spirit, would start to grow. But at that time, 1978, the result obtained only justified the selected method. It was the first time the UCN method displayed its advantages, even at the reactor with an average thermal neutron flux. In order to conduct real studies of the CP-violation problem we had to move further. The perspectives were to increase UCN intensity by using a liquid hydrogen UCN source.

A small-volume liquid hydrogen UCN source [6]

Let hydrogen into reactor? The first thought of it was terrifying. No hydrogen and nuclear safety regulations would allow doing this. And strictness of these regulations justifies itself. Firstly, any possibility of explosive hydrogen-air mixture formation must be eliminated, secondly, still in case of explosion there should be a guarantee of its localization inside a vacuum source case. The probability of emergency case must be less than $10^{-7} – 10^{-8}$ per year.

It was easier to conduct an experimental verification test of the vacuum case strength rather than calculate it. Therefore a channel model equipped with piezoelectric transducers was built. The transducers were used to detect a developed detonation wave inside the channel, to measure the peak pressure on its walls and the pressure transmitted into water at the explosion due to deformation of channel walls. After a series of
unsuccessful attempts to realize a developed detonation mode (as a rule, the mixture only combusted and did not detonate), a detonation tube with a spiral was connected to the model to imitate detonation mode. Finally, we managed to carry out a number of successful detonations. The channel model had kept its tightness properties after detonations and no residual deformation had been observed. At the same time it was shown that the measured values of maximum peak pressure in water would pose no hazard to reactor elements. This fact gave grounds for acquiring a permission for operation of a liquid hydrogen UCN source at the WWR-M reactor. Here it would be appropriate to mention that in the part of safety validations and strength calculations, collaboration with V.I. Didenko and his colleagues turned out to be very useful.

Later on safety regulations became even stricter, especially after the Chernobyl accident. So the time and efforts spent for approval of the design of the next channel – the channel of a universal cold and ultra-cold neutron source – turned out to be comparable with the time spent on its manufacturing. For instance, experimental detonation tests were not sufficient any more. New regulations also demanded calculations to be done proving the correctness of experiments. So we were forced to contact specialists who could calculate the strength of sub-water constructions for certain scenarios. These calculations verified the strength sufficiency of the universal liquid hydrogen neutron source case and showed that in case of an emergency the impact transmitted into water would be negligible, for example, a pulse shift of elements near the source would amount to 16 μ only. These were real practical questions we had to settle in order to be able to conduct fundamental studies with UCN.

Another problem, which is also classified as one of the extreme problems of experimental physics, was to keep hydrogen in a liquid phase under conditions of intense reactor radiation. It was a difficult task, and therefore interesting. In order to obtain the first practical experience in creation of a liquid hydrogen neutron source, a vertical channel in the beryllium reflector, which had a moderate level of heat release comparing to the center of the active zone, was selected. However, the heat release amounted to 300 W in a volume of 250 cm³. To understand what it means, try to imagine a boiler in a glass of hydrogen, and the task is to remove heat at the temperature of 20 K, not allowing hydrogen to boil. An additional requirement was to provide for the strength of the case, not limiting a UCN yield through its walls. The solution found was the following: the moderator case and the heat-exchanger were combined together and represented a tubular construction with a double wall of thin zirconium. The construction elements were made of zirconium alloy and connected by means of electron-beam welding in vacuum. That was a fine piece of work masterfully performed by I.I. Mosichev. So at that time the electron-beam welding was developed and mastered in the PNPI workshop. Also for the source manufacturing purposes a special setup, allowing to perform very complicated operations, was built. Mirror neutron guides made of stainless steel were also welded by an electron beam – it provided for simplicity of construction and for an elegant technical solution of the heat removal problem: the neutron guide, also known as the vacuum containment, was cooled by reactor water, which removed the heat power caused by radiation heating-up.

The second feature of the new method for neutron guide manufacturing was connected with employment of magnetron sputtering and creation of a coating with a high boundary UCN reflection velocity. For this purpose a compact sputtering head of a magnetron type was produced. It could move inside curved parts of a neutron guide and maintain, firstly, plasma stripping of the surface, and then, sputtering of 58Ni isotope. R.R Taldaev and N.V. Borovikova played a substantial role in formation and development of the magnetron sputtering technology. N.V. Borovikova sputtered, probably amounting to a hundred, of square meters of various coatings for neutron guides, EDM-spectrometer chambers, etc. She also mastered a technology of mirror foil production with 58NiMo coating, which was used for neutron guides. Now we have at our service a magnetron technology, which allows to sputter not only plain surfaces but also tubes from inside (M.S. Lasakov, R.R. Taldave), beryllium coatings and beryllium oxide coatings for the EDM-experiment and the neutron lifetime experiment. This entire technological arsenal – anode-mechanical polishing, electron-beam welding, and magnetron sputtering – is the most important component part of the UCN experimental methodology. Without it, it would have been impossible to obtain the best accuracy results in the UCN experiments.

However, let us return to the liquid hydrogen source in the V13 channel. The source was installed in 1980 (Fig. 4). Under cooling of the hydrogen source the temperature gain factor amounted to 25–30 times at the temperature of liquid hydrogen. The task to create a liquid hydrogen source under a heat release of
0.3 W/g due to $\gamma$-quanta and 8 W/g due to fast neutrons was successfully solved with a minimum quantity of liquid hydrogen thanks to cooling mode optimization and sectioning method. Apparently, this case displayed the maximum capabilities of the method of the heat-exchanger chamber. Using these UCN source and EDM-spectrometer with magnetic field stabilization, we managed to obtain the following value of the upper limit of neutron EDM: $|d_{\text{n}}| < 4.6 \times 10^{-25} \text{ e cm}$, that is, by 6 times better than the beam experiment results in Grenoble. The source of this type had been used for 6 years, though due to leakage in the liquid hydrogen chamber we had to manufacture a second one.

**Stabilization of magnetic field [9,13]**

The problem of stabilization of magnetic field in the EDM-spectrometer is a separate independent problem consisting of different stages. Improvement in stability of resonance conditions as well as a progress in UCN intensity increase can be both put on a logarithmic scale.

Firstly, let us explain the difficulty of the task. The sought magnet resonance shift at a field strength of 10 kV/cm and neutron EDM of $10^{-25} \text{ e cm}$ will be $\approx 3 \times 10^{-10} \text{ Oe}$. The resonance width after 100 seconds of UCN storage in the trap will be $10^{-6} \text{ Oe}$. So a magnetic field stability of $10^{-7} - 10^{-8} \text{ Oe}$ is required for the time passing between two switches of electrical field.

When we measured magnetic field fluctuations in the reactor experimental hall, we were terrified, as a typical level of fluctuations amounted to $10^{-3} \text{ Oe}$. Physical setups operating in the hall were the main source of magnetic disturbances. Also starting currents of electric trains from nearest railroads exerted considerable influence. The required factor of neutralization had to be at a level of $10^4 - 10^5$. Approximately three orders of magnitude were provided by a three-layer permalloy screen along with usage of alternating current remagnetization effect. The next step in magnetic field stabilization improvement was connected with creation of stabilization system around the screens. As a supporting element of the system, a flux-gate magnetometer, obtained from some geophysical institute, was used. This system had not long been in existence. It had been replaced with a magnetic field stabilization system inside the screens. This one was based on a quantum cesium magnetometer. The frequency of a self-generating magnetometer could be compared to that of the bearing generator by means of a phase detector. An error signal in form of continuous current entered the coils creating a magnetic field in the spectrometer. This system had been successfully used at one of the stages of the EDM measurements. The average value of magnetic field stability amounted to $3 \times 10^{-7} \text{ Oe}$. However, this system had two disadvantages: it could poorly compensate fluctuations of dissimilar types and had a low operating speed due to inductive currents in a vacuum chamber. Then a very brave attempt, in order to solve all the problems at one stroke, had been taken - an attempt to create a super-conducting screen inside the vacuum chamber. A small 4K refrigerator was produced which used some power from the cold neutron source refrigerator. A super-conducting screen represented a net from a super-conducting wire applied to a cooled copper screen. The result was oppressive: magnetic field fluctuations had increased. Thermal currents were the reason, we had not expected the effect to be so strong. The attempts to change configuration of the system were useless. The nature taught us a lesson punishing us for our haste. So we returned again to the stabilization system based on a cesium magnetometer. At the same time a productive idea was born, it was proposed to obtain the frequency for neutron resonance by dividing the cesium magnetometer frequency on ratio of cesium and neutron magnetic moments. As a matter of fact, we had to stabilize the resonance conditions, therefore tuning of oscillating field frequency was a good decision, moreover it could be done with the necessary operating speed. Further on the system had become more complicated: three bearing magnetometers were used in order to account the effect of inhomogeneous magnetic field changes inside the screen.

In the end the measurement accuracy was determined by the entire set of facilities: differential scheme based on two chambers, polarization double-analysis system, resonance condition stabilization system based on magnetometers. The equivalent value of magnetic field stability amounted to $10^{-8} \text{ Oe}$.

Under such conditions it was already possible to increase the UCN storage time, in order to improve the setup sensitivity. For this purpose, a storage version of the experiment, in which neutrons were kept in the traps with the shutters closed, was conducted. The resonance width decreased by 10 times, but even with such a thin resonance it was still possible to work.
Neutron EDM measurements [4,5,7,10,12]

The acquisition of experimental statistics is always a painful and strained procedure. Occasionally one of the systems fails to operate: either reactor launch is postponed, or there are some problems with the refrigerator (helium purity is not sufficient, liquid nitrogen is not available on time, expander fails to start), and finally, we have neutrons but the EDM-spectrometer system is malfunctioning. Therefore the real time of statistics acquisition is usually by 3-4 times less than the maximum possible one. This ratio of real and available times, called $\pi$ coefficient, has already been long considered as a law and seen as a normal value.

When the measurements were carried out on the universal neutron source, the setup sensitivity was $(2-3) \cdot 10^{-25} \text{ e\cdotcm / day}$ corresponding to an uncertainty of $1 \cdot 10^{-25} \text{ e\cdotcm}$. That was the upper limit for neutron EDM that we managed to obtain experimentally. There were also many other experiments on the universal source. They are described in a separate section.

But prior to ending the EDM-experiment topic, I would like to note contributions of those who, together with the main participants named earlier, provided substantial help for realization of the EDM-experiment. They are V.A. Knyazkov and V.L. Ryabov, who had taken part in early stages of the experiment; E.A. Kolomensky and A.N. Pirozhkov, who joined the process at final stages; E.V. Shulgina, who developed a set of programs for the experiment management. Special thanks are addressed to A.I. Egorov for his continuous creative participation in many stages of work, and to V.A. Nazarenko for his encouragement of the experiment. Electronic support tasks were realized with assistance of V.I. Kadashhevich, V.N. Slyusar, V.G. Muratov, V.V. Marchenkov, L.A. Grigorieva, Ya.A. Kasman, and other members of the nuclear electronics team. The major part of setup design works belongs to N.A. Efimov. Setups were produced at the PNPI workshop (L.Sh. Rabinsky, E.A. Ivanov, A.A. Tsvetnikov, V.N. Verestchagin and others), however, the majority of the works had been carried out in the mechanical shop of the Neutron Research Department by V.A. Priemysh and his colleagues. Installation of setups on the reactor and their maintenance were performed by mechanics from the laboratory of Weak Interaction Research and Neutron Physics laboratory: V.B. Belyakov, N.I. Butusov, N.N. Dmitriev, G.D. Chuklin, Yu.M. Lysenkov, V.A. Radaev, A.A. Tyushev, who provided inestimable assistance at all stages of the experiment.

The universal source of polarized cold and ultra-cold neutrons at the WWR-M reactor [14-16]

The next stage in development of cold neutron sources at the WWR-M reactor is connected with creation of a universal channel that allowed to obtain not only UCN but cold polarized neutrons as well (Fig. 5). On one hand, the insatiable EDM-spectrometer still required UCN intensity increase, on the other, it was time to measure neutron lifetime, which required an independent UCN beam. The possibility to obtain a beam of cold and, of course, polarized neutrons from the liquid hydrogen neutron source was itself very attractive, as it would widen the scope of experimental tasks, such as: precision studies of neutron $\beta$-decay with the purpose of standard model verification; studies of weak nucleon-nucleon interaction; measurements of neutron spin rotation effect in case of passage through a para-hydrogen target; measurements of parity violation effects in neutron-nucleus interactions, etc. At that time (1984), a scientific research program for the PIK reactor was in the stage of development, and the universal source was supposed to provide experimental facilities for preparation of new experiments and for improvement of cold neutron handling techniques.

![Fig. 5. The universal source of polarized cold and ultra-cold neutrons at the WWR-M reactor](image)
The task of building a liquid hydrogen neutron source in the center of the active zone of 18 MW reactor was even more extreme than the previous one. Its solution had no analogues in the worldwide practice. The level of specific heat release in the center of the active zone even in case of employment of a lead screen amounted approximately to 2.5 kW/l (for instance, for a cold source at the high-flux reactor in ILL this value was by an order of magnitude less). It was quite obvious that this power could be removed only by means of liquid hydrogen circulation. The method of a liquid hydrogen chamber-heat-exchanger was inapplicable. The thermo-siphon liquid-vapor scheme used at ILL also could not be used. We needed a reliable circulation pump. It would have been hard to invent something more reliable than a natural convection, therefore the scheme shown in the Fig. 6 was selected. Movement of hydrogen in the loop is caused by hydrostatic forces, which, in their turn, are aroused due to a difference in densities of hydrogen in the right and left parts of the loop. In case of increase of heat supply to the source the speed of circulations rises – so in relation to external heat load the system is self-regulating. When the reactor operated at full power the speed of movement of liquid hydrogen along the loop tubes amounted to 1 m/s. So it turned out to be a very efficient circulation pump.

Of course, for this source we had to solve all the safety problems again – at this time all hydrogen and vacuum communications, located in the reactor hall, were placed into protective helium shells. For purposes of source cooling a new 4 kW helium refrigerator was used. It was installed with assistance of K.A. Kono-plev’s department. A powerful cryogenic provision of the source was possible due to an exclusively important contribution of the cryogenic service employees from the Reactor Physics and Technology Department (G.D. Porsev, V.A. Mityukhlyaev, A.A. Zakharov).

Already in the beginning of source operation we faced some problems. After we had filled the source with hydrogen and subsequently emptied it, a change in the reactor reactivity occurred to be higher than the calculated value and the standards. We managed to eliminate the problem by using a deuterium-hydrogen mixture instead of pure hydrogen. Fortunately, it did not affect the efficiency of neutron thermalization in the source, as the moderator volume was sufficiently large. At the same time (1986) comparable studies of UCN yields from various, hydrogen and deuterium, sources were carried out. The data obtained in these studies would find its application later on in a new initiative – studies of a solid deuterium UCN source. The UCN flux, obtained in the universal channel, amounted to $2.5 \times 10^5$ n/s for each beam of the UCN neutron guide system (Fig. 5). The temperature gain factor of 45 times was a new success on the way of UCN source efficiency improvement.

The built source with the universal neutron guide system beside UCN also allowed to produce cold polarized neutrons, which was very important for fundamental studies. The neutron flux results, spectra and spectral dependences of the gain factor are presented in the Figs. 7,8.

Preliminary calculations and evaluations had shown that there was a chance to extract a flux of polarized cold neutrons and to obtain a higher flux density than that in Grenoble. In the course of measurements it was very pleasant to observe a

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**Fig. 6.** The scheme of a circulation liquid hydrogen loop.
good agreement with calculations. As a matter of fact, we managed to obtain a density of a cold polarized neutron flux and a density of the full flux that were by 5 and 15 times, respectively, greater than those at ILL. This result, obtained at PNPI, remained the best even after a new polarized beam for fundamental studies (PF1) was created at ILL. This fact became apparent in the course of measurements of antineutrino-spin asymmetry of neutron β-decay on the PF1 beam at ILL.

The main feature of our polarizing neutron guide was that it had been designed and optimized especially for extraction of polarized neutrons. B.G. Erozolimsky and I.A. Kuznetsov had played the most active part in the project of the polarizing neutron guide. This project was based on calculation techniques for polarizing neutron guides and technology of their manufacturing, which were developed in the Neutron Research Laboratory by A.F. Schebetov and his colleagues (B.G. Peskov, V.Ya. Kezerashvili and others).

The polarizing neutron guide was placed into a solenoid with a current of 500 A that creates a magnetic field of 500 Oe on Fe-Co mirrors. The lower part of solenoid was cooled by reactor water, the upper – by a special loop with distilled water. Here, the experience of B.G. Erozolimsky, which he obtained in the course of creation of a similar system on the IRT reactor in 70-s, turned out to be very useful.

The UCN neutron guide system for our source was developed with account of requirements of a new neutron lifetime measurement experiment. Therefore, at the point where the neutron guide leaves the reactor chamber, it was divided into two. Additionally, a system of UCN beam redistribution was installed, which allowed to simultaneously conduct three experiments. On the vertical beam it was possible to conduct two
experiments, one above another, as the lower setup, used for neutron β-decay studies, had practically no weakening effect on the beam. The Fig. 9 displays the program of experiments, which were carried out on the universal channel. This figure was plotted in 1988. Since then, an entire series of excellent experimental results with the highest level of accuracy has been obtained on the universal channel.

1. The first limit for neutron EDM obtained – $1.1 \times 10^{-25}$ e·cm (95% C.L.).
2. Correlation coefficient A in β-decay of neutron measured with an accuracy of 1.4% (asymmetry of electron escape in relation to neutron spin).
3. Neutron lifetime measured with an accuracy of 0.3%.
4. Asymmetry of antineutrino escape in relation to neutron spin in the β-decay of the neutron (B) measured with the best accuracy in the world.
5. Parity violation effects in various reactions with neutrons (n, γ; n, α) studied at a level of accuracy that has not yet been obtained in similar experiments.

Fig. 9. The scheme of dislocation of experimental setups on the universal channel of the WWR-M reactor
1 - the magnet-resonance spectrometer for the EDM-experiment, 2 - a setup for neutron lifetime measurement by a method of UCN storage in a gravitational trap (PNPI-JINR), 3 - a neutron microscope (IAE), 4 - a diffraction grating interferometer, 5 - a magnetic correlative spectrometer for neutron β-decay studies by means of UCN, 6 - a setup for measurements of parity violation effects in (n, γ) reaction with polarized neutrons, 7 - a setup for measurements of γ-quanta circular polarization at the capture of polarized neutrons in parahydrogen, 8 - a correlative spectrometer for neutron β-decay studies on a beam of polarized neutrons (PNPI-IAE), 9 - a setup for studies of parity violation effect in reactions with charged particles (PNPI-JINR), 10 - a setup for measurements of the neutron spin precession effect at the passage through parahydrogen, deuterium, helium, etc., 11 - a setup for measurement of T-odd effect in β-decay of neutron (PNPI-IAE)

The majority of the program that was meant for the PIK reactor was carried out on the universal source. The results obtained are in good competition with those obtained at the high-flux ILL reactor. It could be said that the universal source changed the WWR-M reactor status. In any case, it advanced it very close to the level of modern reactors.


Unfortunately, the universal channel is out of operation at present, though a new one has been manufactured and tested in a low-temperature mode. The universal channel mounted on test desk in the main reactor hall has not yet been installed into the reactor. We are now expecting a new refrigerator to be supplied, cost
ing one million dollar that can be obtained from a German credit. It is not possible to use the old refrigerator, as it has no automated control system, due to lack of which already three universal channels have been broken. It would make no sense to try it for the forth time.

There are still chances to obtain a new refrigerator, but our scientific plans are already connected with other neutron sources, which have been and are created in collaboration with PSI.

**Solid deuterium UCN source [17,18]**

It seemed so that all ideas and technical possibilities for further UCN source development had been exhausted, and the UCN density increase function of time, shown in the Fig. 2, was a clear confirmation to that fact. However, we just recently (1994) proposed and experimentally studied a new type of UCN source – solid deuterium at a temperature of liquid helium (Fig. 10).

It appeared to be that at a transition state from a liquid to a solid phase and at a further cooling of already solid deuterium an additional UCN intensity gain factor of 10 could be obtained (Fig. 11). This is the result of an experiment with a solid deuterium source in the channel No10 of the WWR-M reactor. The full factor of a UCN yield increase from room temperature up to the temperature of liquid helium amounted to 1230 times. However, in order to maintain a normal operation of the source at the temperature of liquid helium, a reduced level of radiation heat release must be provided. Heavy water reactors provide the necessary ratio of neutron flux and heat release at the edge of heavy water reflector, therefore this project can be realized for the PIK reactor and also for spallation-sources which have been actively developed lately.

UCN yield gain factor for solid deuterium, or
alternatively a relation of UCN source intensity at different saturated vapor pressures to solid deuterium UCN intensity in vicinity of the triple point temperature (18.7 K) and at a pressure of 200 torr (normalization point) is shown in Fig. 11. Within the range of pressures from 200 to 128 torr a solid phase share varies from 0 to 100% at the temperature of 18.7 K. The gain factor increases approximately by 3 times at the temperature of 18.7 K only due to a solid-state transition; further yield increase is connected with decrease of solid deuterium temperature.

Development, creation and studies of a solid deuterium source have been carried out in collaboration with American scientists J. Green and T. Bowles from Los-Alamos. The American part of contribution to the project realization was significant. The following persons have also taken an active part in the project: V.A. Mityukhlyaeve, A.A. Zakharov, A.G. Kharitonov, M.S. Lasakov, V.E. Varlamov, R.R. Taldaev, A.V. Aldustchenkov, A.V. Vasiliev.

**Precision studies of β-decay of neutron [19-28]**

One of the problems of elementary-particle physics, which must and may be solved on reactors – is a β-decay of the neutron. This process is exceptionally important for the theory. Axial and vector constants of weak interaction can be strictly determined from the β-decay of the neutron. Knowing high accuracy parameters of this process can help verify unitarity of the Kobayashi-Maskawa matrix. Neutron β-decay studies are very important for cosmology and sun model, which, in its turn, is connected with the problem of sun neutrino. However, the β-decay of the neutron has not yet been studied very well, as neutron is the most long-living particle. Even in our powerful beam of polarized cold neutrons the number of registered decays amounts to one per second under geometry conditions that allow to restore kinematics of decay.

Ultra-cold neutrons and the possibility to store them in traps have, of course, sharply changed the situation in neutron lifetime measurements. Although already in 1959 Ya.B. Zeldovich in his work proposed to use UCN storage for neutron lifetime measurement, it has taken years of intense work, and a generation of experimenters in order to obtain an accuracy of 0.3%. Two problems were the keys to the solution of this task: as always, these were UCN intensity and UCN storage time in the trap.

Measurements of β-decay angular correlations provide detailed information about weak interaction. Here it is important to have accurate methodical solutions of the task, and, of course, without a high-intensity beam of polarized cold neutrons this experiment is just not possible. Creation of the universal channel has in many respects determined the accuracy of β-decay asymmetry measurements. In whole, the problem of β-decay studies has been successfully solved at PNPI, though there are still many experimental techniques to try.

After this short preface, I would like, just as I did earlier, to introduce the authors of this research program. A neutron lifetime measurement experiment with a UCN gravitational trap was conceived in 1983. The experimental setup was designed in the PNPI with participation of R.R. Taldaev, and the modeling part was entrusted to V.V. Nesvizhevsky, who, at that time, was a student engaged on a degree thesis. Cryogenic tasks were successfully solved under leadership of A.G. Kharitonov. At that time, he moved to the neutron physics laboratory and joined experimental activities along with physicists. At present time V.E. Varlamov takes an active part in the experiment. The neutron lifetime measurement experiment has been carried out in collaboration with our colleagues from Dubna: A.V. Strelkov, V.P. Alfimenkov, and later on V.N. Shvetsov. These people are very keen on science and have contributed significantly to the experiment. The neutron physics laboratory of JINR provided substantial assistance: the main setup parts were produced in their workshops. It helped to be on schedule, as at that time our workshop was busy with production of the universal channel.

**Neutron lifetime**

This chapter should be started with the problem of keeping UCN in a trap, which, as it was already mentioned, was discovered during the first UCN storage experiments. It was not possible to keep neutrons in a trap for more than a hundred seconds, which meant that the loss probability due to interaction with walls was by 10 times higher than the probability of β-decay. With such losses it is practically impossible to have measurement accuracy better than one percent. It was necessary to make UCN loss probability much less
than the decay probability. In order to achieve this, we had to increase the UCN storage time by not less than two orders of magnitude. The idea was to use the optimum storage mode: neutrons of low energies in gravitational field, pure materials and low temperatures.

In order to obtain a high surface purity, it was planned to freeze oxygen over a beryllium coated trap surface after it has already been warmed up and degassed at high temperatures. Thus the temperature range had to vary from 700 K to 10 K. Under such conditions it was hard to make a reliable and tightly closing shutter. Therefore the idea of a gravitational shutter, discussed in former times by P.E. Spivak, was used. It became clear that using a sphere with an opening, which could turn around a horizontal axis, we could make a gravitational spectrometer (see Fig. 12). This would allow to measure storage time depending on a neutron energy and to separate losses in walls from $\beta$-decay, as the loss probability depends on neutron velocity, and decay probability, of course does not. In case of a victory over a so-called UCN storage anomaly, that was rather close, we could expect the losses to be much less than that of $\beta$-decay probability. It would allow to measure almost directly the exponent of neutron decay. We mainly counted on the frozen oxygen.

The scheme of the experiment is shown in the Fig. 12. UCN fill the spherical trap, when its opening points downwards. After that the trap is turned over and neutrons with low kinetic energy can not jump out of it due to the gravitational field effect, the quality of gravitational shutter guaranteed. After neutrons have been kept in the trap for a given period of time, the trap is turned to an angle, and the neutrons with the highest kinetic energy pop out of the trap, get accelerated in the gravitational field and reach the detector. Then, step by step, angle by angle, the procedure is repeated until the last neutron leaves the trap. After that, the entire set of operations discussed above is repeated for another value of storage time. Taking into account that every time the trap is filled under the same conditions (15 thousand UCN were captured, as a rule), then, by varying the storage time we get a different value of non-decayed neutrons, in other words, the exponent of $\beta$-decay, considering that UCN losses in walls are negligible.

The setup drawing presented here was made as early as the stage of the experiment idea formation, and, just for fun, the setup was drawn in an old-fashioned style, in order to underline the peculiarity of the method. The technical realization of the idea differs a bit: there are no chain-drives and motors inside the vacuum volume. Transmission is provided by stepping motors that are, of course, located outside, and transmission inside the trap between two vacuum volumes is provided by silphons with a very large stroke, which were produced on a special request. However, the general idea of the experiment can be better apprehended from this very drawing. That is why it was also used for publications.

At the start of the experiment we decided to obtain a good storage time by means of very low temperatures (10 K) and a beryllium coated trap only, without using frozen oxygen and even without a warm-up. Almost all phonons were supposed to be frozen out, and then hydrogen would be no threat. The UCN storage time amounted to 844 seconds (loss probability – 5% of $\beta$-decay probability). A new practical result was

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**Fig. 12.** The experimental setup scheme:

1 - a UCN trap, 2 - a nitrogen screen, 3 - a distribution valve, 4, 9 - neutron guides for intake and output of UCN, 5 - incoming shutter, 6 - a detector, 7 - detector protection, 8 - valve and trap operating system, 10 - cryopipes, 11 - a cryostatting volume, 12 - a gateway of a system for freezing coatings inside the trap.
obtained, but it was quite far away from the theory of UCN storage. Of course, in order to get a clear result it was necessary to clean the surface and warm up the trap. At least we hoped that would help. We had warmed up the trap for 5 days. We had also washed it with a gaseous helium, which, in order to preserve the high purity, was supplied from a dewar. After that the surface was deuterated. It was necessary to replace the odious hydrogen with deuterium. As a matter of fact, an increase of storage time at high temperatures was remarkable. We started the cooling process and the measured temperature dependence of storage time was in parallel with the theoretical one, just a little bit higher. We expected the function to turn into zero losses at zero temperature and continued to freeze the system for 2 days more. Our expectations had not come true, again we had the storage time of 845 seconds. We removed hydrogen, it was obvious, but the final result had not changed. Then we tried to sputter oxygen, storage time obtained was 872 seconds. It was, of course, the loss time that had never been obtained before, approximately 8 hours, or 3% of the $\beta$-decay probability. But difference with the theory was still about two orders of magnitude. It was quite an intriguing situation, we had to choose: storage anomaly research or neutron lifetime measurements. Loss probability was only 3% of $\beta$-decay, which is a nearly direct observation of the decay exponent. As a matter of fact, an ecologically clean environment was created for neutrons. It was a good chance to use it for neutron lifetime measurements. We carried out an experiment with a spherical beryllium coated trap made of aluminum and with frozen oxygen. Then we made another experiment, but at this time, with a flat cylindrical trap, in order to increase the accuracy of extrapolation zero probability of interaction of UCN with walls. The result of this extrapolation is shown in the Fig. 13. The neutron lifetime was measured with an accuracy of approximately 0.4% ($888.4 \pm 3.3$ s). Besides the high accuracy value, this experiment was remarkable for the fact that we had the minimum value of correction connected with UCN losses during storage, and possible systematic error was less than statistical one.

Anomalous losses during UCN storage

Now let us return to the question of UCN storage anomaly, which we brought up in the course of a fight for the maximum possible UCN storage time. Then we obtained an amazing result. The cross-section of neutron interaction with substance, which was determined from the UCN reflection losses and from the passage of neutrons through the substance, turned out to have a systematical difference of approximately 1 barn (Fig. 14). This value corresponds with the value of UCN reflection loss probability $3 \times 10^{-5}$.

In order to verify this phenomenon, even a whole beryllium trap was produced. But it gave the same result as a beryllium coated trap. There was a possibility of penetration through a beryllium foil, but it was also verified and eliminated. There have been a lot of attempts to reveal the nature of these losses, but it still remains a secret. Now almost all research teams working with UCN have been involved into this problem.

Fig. 13. Dependence of reversed storage time on effective frequency of UCN collisions with trap walls
○ - measurements with a spherical trap,
● - measurements with a cylindrical trap;
1 (Be) - beryllium coated traps,
2 ($O_2$) - oxygen coated traps
In attempt to find the answer we have recently carried out an experiment at ILL, in which we tried to discover a low-energy heating of UCN. However, we have not discovered it. And that result actually intrigued us. One of the possible explanations was that due to incoherent scattering a UCN gets inside a substance, where it gets localized, because its effective kinetic energy in substance is negative. A new experiment was to verify this hypothesis. First experiments of UCN depolarization measurements during their storage in substance traps proved presence of incoherent scattering process at UCN reflection due to neutron spin-flip. The probability of a UCN spin-flip at reflection from substance also turned out to be at the level of $10^{-5}$ per one collision with surface. The hypothesis is very likely to be true, however more accurate results are required for its final confirmation. It is necessary to measure a ratio of an anomalous loss probability to a probability of a spin-flip in one experiment.

**Measurements of the angular correlations in neutron β-decay**

The second and very important part of the neutron β-decay research program – is the measurement of angular correlations. In 1982, B.G. Erozolimsky, who together with Yu.A. Mostovoy had thoroughly studied β-decay of neutron in IAE, decided to come to PNPI. Within our laboratory we formed a team led by B.G. Erozolimsky and invited young physicists: I.A. Kuznetsov, and later on – N.F. Maslov. The latter, unfortunately, untimely passed away leaving a very good memory. After that I.V. Stepanenko joined us and successfully took charge of software support of the experiment. O.V. Rozhnov, a radio engineer, is one of the team members and also assists us in the experiment. N.V. Romanenko is consulted for many theoretical questions. Unfortunately, in 1991 B.G. Erozolimsky moved to USA, though he can still take part in our works. When we faced the task of neutron polarization measurements, M.S. Lasakov and A.V. Adlustchenkov joined the process. Then we formed a collaboration with the American National Institute for Standards and Technology. M. S. Dewey is a representative of the American side in the experiment of $B$-asymmetry measurement. This team carried out the experiment of antineutrino-spin asymmetry measurement on a high-flux reactor in Grenoble.

But the first experiment for angular correlation measurements was carried out on the universal channel. Firstly, asymmetry of electron escape in relation to neutron spin direction ($A$-asymmetry) was measured. An accuracy of B.G. Erozolimsky’s experiment was better than that of the ILL experiment. The statistical accuracy of the experiment was guaranteed by a high intensity of a neutron beam. Experimental methods had already been to a great extent developed and tested in previous experiments, however it had taken two years to obtain the result. The experiment required a series of check tests to be conducted, which were connected with full focusing of decay protons, and also with a quite difficult task – measurement of polarization of a neutron beam. These measurements were carried out with the help of a mirror-analyzer that was calibrated by the Stern-Gerlach method.

The results of the correlation coefficient $A$ and the neutron lifetime measurements carried out in Gatchina and Grenoble allowed to determine a weak interaction vector constant from neutron β-decay with a
The same work had to be done again, now without any creative interest. As a whole, it was a very wide and costs spent on manufacturing just vanished in the haze. No restoration was possible due to a very high activation loss of a source was a real tragedy, as all experimental plans were destroyed in a moment, immense efforts only 4 days. The measurements had been interrupted in the very beginning and the source had been lost. A freezing point. By the moment of this tragic failure the pure time of statistics acquisition had amounted to had taken more than half a year to move away from experimental problems on to real measurements. But as

right-handed currents influence on the process of \( \beta \)-decay. We also got involved into the analysis of the right-handed currents problem and suggested our explanation with a heavy right-handed muon neutrino. The problem lied in that the limits for the right-handed vector boson \( W_R \) from the muon experiment made it difficult to build such explanations. Employment of the heavy right-handed muon neutrino allowed to solve this contradiction. Honestly speaking, all this was interesting only from the point of a deeper understanding of the weak interaction standard model. The main conclusion of this analysis was that we needed to measure the antineutrino escape asymmetry in relation to neutron spin (B-asymmetry) with a better accuracy. This experiment is a direct test for left-right models. As a matter of fact, B-asymmetry can be predicted by a standard model with an accuracy of \( 10^{-3} \). A previous experiment for B-asymmetry measurement was done with an accuracy of 3.5\%, and we set out a task to increase the accuracy by an order of magnitude.

The same setup that is used for A-asymmetry measurement can be also used for measurements of B-asymmetry, if a flight base is additionally created for recoil protons in order to measure their pulses by the time-of-flight method. This idea of the setup modification was suggested by B.G. Erozolimsky many years ago. The main problem that made it difficult to obtain the necessary accuracy was to provide the accuracy of the time-of-flight method. The solution was to use micro-channel plates of large square. Such plates are used in night-vision devices, they have outstanding time properties. We were very lucky to get the quantity we needed. Electronic equipment of the experiment was provided by the department of V.V. Marchenkov. In the beginning, it required thorough maintenance, but finally it had successfully passed the tests in Grenoble.

Measurement of neutron beam polarization for this experiment was a new and interesting experimental task. Polarization measurement accuracy at the level of \( 10^{-3} \) was required. But it was especially difficult to obtain it due to a high spectral dependence of the polarization, large angular divergence of the beam and a large square of the cross-section. Generally speaking, neutron beam polarization is, as a rule, evaluated, and not accurately measured, basing, for instance, on an assumption that polarizer and analyzer properties are equivalent. In the polarizer-flipper-analyzer scheme the task of an accurate measurement of polarization was not supposed to be solved at all. The number of measurements in the experiment was less than the number of unknown parameters. Solution of the polarization measurement task came up on a sudden, and, as always by a lucky chance. A scheme with two analyzers and a flipper between them was verified. The calculation techniques had already been developed earlier in polarization analysis with UCN. However illogical it seemed but a more sophisticated scheme and a greater number of unknown parameters helped solve the task. It turned out to be that with two flippers and two analyzers it was possible not only to measure neutron beam polarization but also to determine the properties of analyzers. Now the number of measurements was sufficient for determination of all unknown parameters. Of course, we did not want to stop at this point – we wanted to solve the most general case of the task, when transitions between two spin components of the neutron beam are possible. However, the task of polarization measurement with an accuracy of 0.2\% was solved, as the effect of depolarization turned out to be less than \( 10^{-3} \).

Measurements of B-asymmetry were carried out on the vertical channel with a liquid hydrogen source. It had taken more than half a year to move away from experimental problems on to real measurements. But as soon as we started to acquire statistics, the liquid hydrogen source broke as it got cooled under a hydrogen freezing point. By the moment of this tragic failure the pure time of statistics acquisition had amounted to only 4 days. The measurements had been interrupted in the very beginning and the source had been lost. A loss of a source was a real tragedy, as all experimental plans were destroyed in a moment, immense efforts and costs spent on manufacturing just vanished in the haze. No restoration was possible due to a very high activation of the channel. Creation of a new source would take years and funds that we firstly needed to find. The same work had to be done again, now without any creative interest. As a whole, it was a very wide

significantly increased accuracy. The most accurate method for determination of the weak interaction vector constant \( G_V \) has so far been the method of measurement of probabilities of Fermi superallowed \( 0^- \to 0^- \) transitions. Experimental accuracy of this method is very high, however there is some uncertainty due to nuclear corrections, because nuclear calculations depend on a model. Therefore the value of \( G_V \) extracted from an elementary process of neutron decay is very significant. The progress done in experimental studies of neutron \( \beta \)-decay allowed to determine the weak interaction vector constant directly from this process. However, there was a discrepancy in the new value amounting to 3.5 standard deviations. Although it was not a great discrepancy, the fact raised a lot of discussions and a few publications, which analyzed a possibility of right-handed currents influence on the process of \( \beta \)-decay. We also got involved into the analysis of the right-handed currents problem and suggested our explanation with a heavy right-handed muon neutrino. The problem lied in that the limits for the right-handed vector boson \( W_R \) from the muon experiment made it difficult to build such explanations. Employment of the heavy right-handed muon neutrino allowed to solve this contradiction. Honestly speaking, all this was interesting only from the point of a deeper understanding of the weak interaction standard model. The main conclusion of this analysis was that we needed to measure the antineutrino escape asymmetry in relation to neutron spin (B-asymmetry) with a better accuracy. This experiment is a direct test for left-right models. As a matter of fact, B-asymmetry can be predicted by a standard model with an accuracy of \( 10^{-3} \). A previous experiment for B-asymmetry measurement was done with an accuracy of 3.5\%, and we set out a task to increase the accuracy by an order of magnitude.

The same setup that is used for A-asymmetry measurement can be also used for measurements of B-asymmetry, if a flight base is additionally created for recoil protons in order to measure their pulses by the time-of-flight method. This idea of the setup modification was suggested by B.G. Erozolimsky many years ago. The main problem that made it difficult to obtain the necessary accuracy was to provide the accuracy of the time-of-flight method. The solution was to use micro-channel plates of large square. Such plates are used in night-vision devices, they have outstanding time properties. We were very lucky to get the quantity we needed. Electronic equipment of the experiment was provided by the department of V.V. Marchenkov. In the beginning, it required thorough maintenance, but finally it had successfully passed the tests in Grenoble.

Measurement of neutron beam polarization for this experiment was a new and interesting experimental task. Polarization measurement accuracy at the level of \( 10^{-3} \) was required. But it was especially difficult to obtain it due to a high spectral dependence of the polarization, large angular divergence of the beam and a large square of the cross-section. Generally speaking, neutron beam polarization is, as a rule, evaluated, and not accurately measured, basing, for instance, on an assumption that polarizer and analyzer properties are equivalent. In the polarizer-flipper-analyzer scheme the task of an accurate measurement of polarization was not supposed to be solved at all. The number of measurements in the experiment was less than the number of unknown parameters. Solution of the polarization measurement task came up on a sudden, and, as always by a lucky chance. A scheme with two analyzers and a flipper between them was verified. The calculation techniques had already been developed earlier in polarization analysis with UCN. However illogical it seemed but a more sophisticated scheme and a greater number of unknown parameters helped solve the task. It turned out to be that with two flippers and two analyzers it was possible not only to measure neutron beam polarization but also to determine the properties of analyzers. Now the number of measurements was sufficient for determination of all unknown parameters. Of course, we did not want to stop at this point – we wanted to solve the most general case of the task, when transitions between two spin components of the neutron beam are possible. However, the task of polarization measurement with an accuracy of 0.2\% was solved, as the effect of depolarization turned out to be less than \( 10^{-3} \).

Measurements of B-asymmetry were carried out on the vertical channel with a liquid hydrogen source. It had taken more than half a year to move away from experimental problems on to real measurements. But as soon as we started to acquire statistics, the liquid hydrogen source broke as it got cooled under a hydrogen freezing point. By the moment of this tragic failure the pure time of statistics acquisition had amounted to only 4 days. The measurements had been interrupted in the very beginning and the source had been lost. A loss of a source was a real tragedy, as all experimental plans were destroyed in a moment, immense efforts and costs spent on manufacturing just vanished in the haze. No restoration was possible due to a very high activation of the channel. Creation of a new source would take years and funds that we firstly needed to find. The same work had to be done again, now without any creative interest. As a whole, it was a very wide

...
spectrum of negative emotions that could cause a depression. But time and work heal, as new problems arise.
In such situations, it is very important to have people who are ready to make all the hard way through again.
A.N. Pirozhkov and E.A. Kolomensky were those who took active part in the works. Also substantial assistance was provided by V.A. Nazarenko. The universal channel of polarized cold and ultra-cold neutrons just had to operate on the WWR-M reactor. So the started research program just could not be stopped, and it just could not be so that the best in the world beam of polarized neutrons would not start operating again.

During the time when our own facilities were not operating, we could fortunately use the beam of polarized neutrons in Grenoble, where the reactor had been relaunched after repair works. But before describing B-asymmetry measurements in Grenoble, let us return to what we had acquired in Gatchina for four days before the source failure. As a matter of fact, even for this time of measurements we had obtained quite a good result, which made our life a little better in these months after the tragedy.

\[ \delta = \left( \frac{M_1}{M_2} \right)^2 \]

![Figure 15. Limits for left-right symmetrical models from experimental data:](image)

1 – dark area from measurements of \( \lambda_T \) and \( \lambda_A \) in neutron and \(^{19}\text{Ne} \) systems; 2 – the same, but with incomplete account of neutron data; 3 – dark area in the bottom of the figure is limit result from the B-asymmetry experiment carried out in Gatchina

The four days, or to be more exact, 93 hours of measurements gave a fourfold increase of B-asymmetry accuracy and allowed to eliminate the right-handed currents hypothesis. The measurement accuracy of antineutrino escape asymmetry in relation to neutron spin amounted to 0.83%. It was a good result for an undetectable particle and gave undependable limit for the mass of a right-handed vector boson from neutron \( \beta \)-decay at a level of 300 GeV/c\(^2\) (Fig. 15). Accuracy limits were mainly determined by statistics. The newly introduced method for polarization measurement turned out to be successful.

It was reasonable to continue the experiment. Therefore we applied for conduction of this experiment on the high-flux reactor in Grenoble. A positive decision for 67 days of measurements was received from the scientific committee. The setup was modified for measurements on a horizontal beam, and also a new setup was built for polarization measurements.

The experiment in Grenoble started with a threatening problem – the polarized neutron beam intensity appeared to be by 20 times less than that in Gatchina, and the polarized neutron flux density – by 10–5 times less. It seemed so that we could pack our suitcases and leave, as under such conditions we would not be able to even reach the four-day Gatchina result. Intermediate measurements of neutron flux density before and after a polarizer, and also after a non-magnetic neutron guide showed that the main losses occurred on the Grenoble non-magnetic neutron guide. A new alternative of the scheme reconstruction was developed, which required 2 meters of a neutron guide made of \(^{58}\text{Ni} \) with a cut of 5 \( \times \) 12 cm\(^2\). The necessary neutron guide section was found in ILL, and the scheme was completely reconstructed. For a non-magnetic part of the neutron guide with flippers a Gatchina section coated by \(^{58}\text{NiMo} \) was used. As a result, the polarized neutron flux density in Grenoble increased by 5 times. Although a counting rate was still by 3 times less than in Gatchina, we could start the experiment, as a good effect-to-background ratio significantly increased the sensitivity of the experimental setup. The efforts spent did not go in vain – we managed to increase the statistical accuracy of measurements by 3 times. B-asymmetry result was doubled and amounted to 0.4%. No significant deviations from the Standard model were discovered. We also managed to improve the limit of the right-handed W-boson. Thus, thanks to our measurements in Gatchina and Grenoble, the accuracy of B-asymmetry was increased almost by an order of magnitude.
The perspective of β-decay precision studies is a direct measurement of axial and vector constants ratio from a ratio of correlation coefficients A and B. The problem of the discussed discrepancy must be solved. Finally, a measurement of the correlation coefficient D, which is responsible for T-violation, is very interesting as well. Besides, the task of the T-violation search in neutron β-decay is quite important, though, may be not so popular as the neutron EDM search. With the D-coefficient accuracy of $10^{-4}$ it is possible to make conclusions about CP-violation problem that are comparable to those made from the neutron EDM measurements with an accuracy of $10^{-25}$ e·cm. Of course, such conclusions are dependent on a model, but nevertheless they are still important. In whole, it is worth studying neutron β-decay.

**Measurement of a neutron spin rotation effect caused by weak interaction [29, 30]**

This experiment was carried out 5 years ago, however it has a very long pre-history.

In the beginning of 80-s a neutron spin rotation effect caused by weak interaction was discovered at ILL. In Russia it was explained by O. Sushkov and V. Flambaum. Then it was experimentally shown that effects in a thermal area amounting to $10^{-4} - 10^{-5}$ were just an echo of resonance effects that can amount to 10%. Transmission asymmetry of polarized neutrons was measured in Dubna at a $p$-wave resonance of 0.74 eV $^{139}$La and amounted to 10%. But the transmission asymmetry was only a half of the entire phenomenon, another half was neutron spin rotation in the vicinity of the resonance. A number of experimental groups set out the task to measure this effect: in Japan on a pulse neutron source, in USA in Los-Alamos on the most powerful pulse neutron source in the world. However, it was successfully and in a simple way solved in Gatchina at the WWR-M reactor. The works were carried out in collaboration with the laboratory of G.A. Petrov, and with an active participation of A.K. Petukhov, G.V. Valsky, Yu.S. Pleva and others.

Everything started with an attempt to form a new direction of studies—search of T-violation in neutron reactions. P-violation enhanced effects stimulated the search of CP-violation enhanced effects on polarized nuclear targets. However, it was decided to test firstly the setup with an unpolarized target. At the same time it became clear that the same experimental scheme would allow to measure the spin rotation effect after a little modification. So we decided to postpone methodical studies of CP-violation experiment and to measure P-odd rotation effect at a resonance energy. The experimental scheme is shown in the Fig. 16. The magnetized crystal is used to obtain polarization and determine the necessary energy range. The same crystal is used for polarization analysis. The crystal-diffraction techniques turned out to be a very effective and simple solution of this task comparing to the scheme with two polarized proton targets.

**Fig. 16.** The experimental setup scheme:

1 - multi-slit collimator, 2 - a magnet with a polarizing crystal, 3, 12 - adiabatic flippers, 4, 11 - averaging coils, 5 - X-solenoid, 6 - a double-layer magnet screen, 7 - Y-solenoid, 8, 10 - Z-solenoids, 9 - $^{139}$La-target, 13 - a magnet with an analyzing crystal, 14 - a neutron detector
The result of measurements obtained in the course of one reactor-cycle is shown in the Fig. 17. To be more exact, the reactor-cycle was prolonged by 3 days more, in order to finish the measurements of the second part of the energy dependence. The neutron spin rotation effect caused by weak interaction is quite strong in the vicinity of the resonance and is equivalent to magnetic field of $0.2 - 0.3\ Oe$, that is comparable with the Earth magnetic field. Besides an excellent physical phenomenon, the efficiency of crystal-diffraction techniques was displayed. These techniques can be used for the search of T-violation interaction. The luminosity can be increased by using advantages of a high flux reactor with a hot neutron source and by using a $^3\text{He}$ polarized target for polarization analysis. Such a setup was prepared for the experiment in Grenoble. This experiment allowed to study the form of resonance dependence of the effect in details and also to evaluate the perspectives of the experiments for the search of T-violation.

**Perspectives for neutron β-decay experimental studies**

As we had no possibility to use our own universal channel on the WWR-M reactor, we bent our efforts to the search of other alternative solutions, such as employment of experimental facilities of the high flux reactor at ILL and creation of new facilities at PSI.

Thanks to good creative and friendly contacts with J. Sromicky a new facilities project was born for polarized cold neutrons at SINQ in PSI. The project was carried out by a collaboration of PNPI, PSI and ETH. A polarizing neutron guide was installed in summer of 1999 (Fig. 18). On the part of PNPI a significant role was played by the team of A.F. Schebetov.

![Fig. 17. Experimental results (points) in comparison with theoretical predictions (curves): a - CP-violating dichroism, b - CP-violating precession. Dotted line shows the ideal energetic resolution, solid lines are real energetic resolution](image1.png)

![Fig. 18. Layout of the polarized cold neutron facility at PSI](image2.png)
At the neutron guide outlet a polarized neutron flux of $4.3 \cdot 10^{10}$ n/s was obtained with a flux density of $7.2 \cdot 10^8$ n/cm$^2$·s. This density is equal to the density of polarized cold neutron flux at the PF1 beam of the high-flux reactor at ILL, in spite of the fact that the initial density of the neutron flux is by 20 times less. A new scheme for extraction of polarized cold neutrons was used at PSI. The scheme difference is that the polarizer is installed as close to the source as possible in a biological shielding of SINQ, after the polarizer a neutron guide-condenser with a guiding magnetic field is installed. In this scheme the polarizer not only prepares polarization but also deflects a beam of polarized cold neutrons. Thus beams of cold neutrons and fast neutrons with γ-quanta are divided at the short distance and we have the best efficiency of extraction of polarized cold neutrons.

The proton current has been recently increased at PSI and they also have replaced the spallation target with a more effective one. As a result, the neutron intensity has been increased by 1.5 times. Thus the polarized cold neutron flux density at PSI is, at present, the best.

At this beam J. Sromicky initiated preparation works for the experimental measurements of the R-coefficient in neutron β-decay. The part of PNPI in this experiment is quite small – measurement of neutron beam polarization.

The aim of PNPI is to measure the correlation coefficients A and B with an accuracy of $10^{-3}$ by means of a magnet correlative spectrometer. Such spectrometer is at present developed at PNPI on the basis of a 5-m super-conductive solenoid. The main element of the setup, a super-conductive solenoid with a magnet plug, has already been produced and is now under cryogenic tests.

The next step of our collaboration is aimed at the development of an universal spectrometer for the investigation of asymmetries in the neutron beta decay. The universality of the spectrometer gives the possibility to use this spectrometer for the measurement of all asymmetry coefficients (A, B, a) in the neutron beta decay simultaneously. The spectrometer has two distinctive features: the first is the magnetic collimation of decay electrons, the second is the usage of time-of-flight method for the measurement of the proton momentum. These features allow to reconstruct the kinematics of a decay event and to determine the direction of antineutrino escape. The reconstruction of decay kinematics gives the possibility for the measurement of all asymmetry coefficients in neutron beta-decay. The magnetic collimation of decay electrons is determined by a ratio of a magnetic field of 3 T to the value of a homogeneous magnetic field (0.3 T) in the decay region.

The value of the collimation angle is $20^\circ$. The decay protons should be accelerated up to 25 keV in order to be registered with the proton detector (pos. 5 in Fig. 19, the basis of the proton detector is micro channel plate). The protons are accelerated in the electric field gradient between the cylinder electrode (pos. 2 in Fig. 19) of decay region and the proton detector. The decay electrons passed through the magnetic collimator are registered with the semiconductor detector (pos. 4 in Fig. 19). Both electron and proton detectors are sectioned. This allows to increase the effect-to-background ratio. Pulses from the electron detector are used as start pulses for the measurement of the proton momentum with the time-of-flight method. The method of delayed coincidence is used to determine the background of accidental coincidences.

![Universal spectrometer for the investigation of asymmetries in the neutron beta decay](image-url)
The realization of this program mainly depends on financing of the project and on possible collaboration schemes. Although the task of precision measurements of neutron $\beta$-decay for the purposes of Standard Model verification and the search for possible deviations is very important and interesting, nevertheless in the laboratory it has the second priority, as the first priority is given to the EDM experiment. The next chapter is devoted to the perspectives of the EDM experiment.

**Perspectives of the EDM search experiment**

Studies with a solid deuterium UCN source, carried out at PNPI, showed that there was a possibility to build more intensive UCN sources at a temperature level of 4K with a gain factor of 1200. It is virtually impossible to sustain a low temperature under a high level of heat release which comes along with high neutron fluxes. Therefore it was initially planned to install a solid deuterium moderator on the edge of a heavy water reflector, where heat release is quite low and a neutron flux is quite high. Afterwards an idea of a pulse mode on a neutron spallation source was considered, which appeared to be more productive. At this time we had a very effective cooperation with J. Sromisky. And finally the UCN factory idea was born.

So far a conceptual design of the UCN factory has been developed, the installation site – prepared, and a proton beam line mounted. The main role in these works have been played by, on the part of PNPI: A. Serebrov, I. Potapov, A. Fomin, A. Kharitonov, V. Mityukhlyaev, A. Zakharov, M. Lasakov, M. Sazhin, D. Tytz, A. Murashkin, and on the part of PSI: M. Daum, R. Henneck, U. Rohrer, K. Kirch, G. Heidenreich, H. Obermeier, H.J. Temnitzer, K. Kohlik, F. Atchison, St. Joray, Ch. Perret and others.

The basic concept of the PSI-PNPI UCN source is a pulsed production of UCN from solid deuterium. Fig. 20 shows a pre-engineering drawing of the UCN source. Neutrons of 2 MeV average energy are

![Pre-engineering drawing of the PSI-PNPI UCN source](image)

The proton beam is delivered through the tube from the left-back. The spallation target is centered in the D$_2$O below the cryogenic insert which holds the SD$_2$ moderator. UCN are guided ($^{58}$Ni coated guide) from their place of production upwards into a Be coated storage vessel. Flapper valves separate the production guide and the storage trap and are closed after the production pulse. UCN can be extracted from the storage into experiments by the guide tubes at the bottom of the storage vessel.
produced on a lead spallation target in a macro-pulse (up to 4 s length) of the full PSI proton beam (590 MeV, 2 mA). There can be more beam pulses, but the total average proton beam current is limited to 10 µA due to the shielding of the area. The spallation neutrons are slowed down and reflected in a large heavy water moderator tank. A block of solid deuterium (SD₂) is placed in the center of the D₂O and serves as a cold moderator for the production of a high cold neutron flux. UCN are produced in the SD₂ by down scattering of cold neutrons and are extracted from the top layer (several cm) of the SD₂ into a large storage volume (2 m³). The UCN producing SD₂ layer will be operated below 8 K temperature, if possible around 6 K. The lower the temperature the more the reverse process of UCN upscattering can be suppressed. Care has to be taken to insure a good quality of the SD₂ moderator with respect to low ¹H contamination and low para-D₂ fraction. The importance of these quality aspects has been investigated recently. The UCN from a proton pulse are extracted upwards by means of a ⁵⁸Ni coated guide into a Be coated storage volume. The production region will after the extraction be separated from the storage region by closing Be coated flapper valves. UCN can be extracted into experiments through a number of guide tubes, 5 of which are forseen to feed the first planned physics experiment, the search for an EDM of the neutron.

Currently the interest in the search for electric dipole moments is increasing again. With a two order of magnitude improvement in sensitivity for the neutron EDM experiments, it will be possible to test a large part of the supersymmetric parameter space to be investigated with the next collider generation. While the standard model prediction for the neutron EDM is about 10⁻³¹ e·cm, there is a good possibility to find it above 10⁻²⁷ e·cm in presently favoured models. The present best published limits on the neutron EDM are around dₙ<10⁻²⁵ e·cm for which the limitations dominantly come from too low statistics. Therefore, there are two avenues for improvements: the first one is to increase the UCN density, and the second one is to increase the volume of the EDM apparatus. Our proposed EDM experiment will take advantage of both approaches. As previously described, there will be an average UCN density of 2400 cm⁻³ available in the storage volume. This translates into a density of 1600 cm⁻³ in our EDM experiment and can be compared to a number of about 6 cm⁻³ in the currently operated EDM experiment at ILL. The experimental volume of our proposed experiment will be 220 l as compared to 20 l.

The sensitivity of an EDM experiment is \( \Delta d_n \sim \left( \sqrt{N} \frac{E P}{\tau} \right)^{-1} \), where \( d_n \) - the EDM, \( N \) - the sample statistic, \( E \) - the electric field strength, \( P \) - the neutron polarization, \( \tau \) - the observation time.

In order to access the sensitivity of our proposed EDM experiment we consider improvements over the currently running experiment, which shows sensitivities on the order of \( \Delta d_n \approx 5 \cdot 10^{-26} \ e\cdot cm \). We denote the factors of improvement for our experiment by 1) \( F_{\sqrt{N}} \), 2) \( F_E \), 3) \( F_{P_f} \), and 4) \( F_{\tau} \), respectively. 1) We have chambers without electrical field for systematic checks. Both chamber types yield about the same statistics and it is planned to subtract their results in the analysis. We therefore do not gain the full statistical factor coming from the density and volume increase, but \( 1/\sqrt{2} \) of it. \( F_{\sqrt{N}}=38 \). 2) The electric field in the ILL experiment is limited to 8 kV/cm due to the Hg co-magnetometer. The former PNPI experiment was operated at 15 kV/cm⁻¹. Our experiment will run with 15 kV/cm⁻¹ and, therefore, \( F_E=1.9 \). 3) Our experiment will have less depolarization of the neutrons in wall collisions, because no compromise for the wall coating has to be made for an additional co-magnetometer. We estimate \( F_{p_f}=1.3 \). 4) Due to a lesser polarization loss, a slightly longer storage time will be possible, yielding a moderate improvement of \( F_{\tau}=1.1 \). Overall, we obtain \( F_{\sqrt{N}}F_EF_{P_f}F_{\tau} \approx 100 \), which corresponds to a sensitivity of \( \Delta d_n \approx 5 \cdot 10^{-28} \ e\cdot cm \).

At this level of sensitivity there is a number of systematic effects, which might influence the experiment. It is of course absolutely necessary to provide a stable magnetic environment and a resonance stabilization, which will be based on 16 Cs-magnetometers placed next to the measurement chambers. Most crucial are the systematic effects with a potential to mimic an EDM effect, thus giving a false positive result. The scheme proposed for our experiment (Fig. 21) has the capability to check on all these systematic effects. A scheme with double chambers, in which the electric field in one half is opposite to the other, greatly reduces the influence of spatially homogeneous magnetic field fluctuations. A set of 4 double chambers allows magnetic
field fluctuations with gradients to be handled, the most nasty of which might be caused by leakage currents.

Fig. 21. A schematic view of the planned EDM spectrometer. 5 guide tubes from the storage volume feed UCN through polarizers into the EDM apparatus, filling the 4 double high voltage chambers and the 5 control chambers without electric field. The magnetic field needed for the EDM experiment is provided by a solenoid which sits in an elaborate magnetic shielding. Only the 4 layers of the passive shielding are shown.
Any leakage current in one chamber will be seen with decreasing signal amplitude in the neighboring chambers. The chambers without electric field, sandwiching the measurement chambers, provide a close additional magnetometer system. An in-situ magnetometer is also given by the neutrons in the measurement chamber themselves, where one can add signals from the differential chambers in order to cancel the high voltage induced effects. Detailed Monte Carlo studies of a variety of systematic effects and their possible treatment are under way. The magnetic field homogeneity and stability themselves are subjects of demonstration experiments which are presently set up.

The UCN source project at PSI and the preparations for the EDM experiment are making good progress. The proton beam line to the UCN source has been put into place during the last shutdown in early 2001. Most of the shielding for the source and the experimental area is already in place. The modifications to the main proton beam line, which are needed in order to put in the fast kicker magnet, will take place during the next shutdown in early 2002. It will then be possible to insert the kicker magnet in a regular two days service break in summer 2002. Presently the investigations concentrate on the following important points: 1) magnetic field control and resonance stabilization for the EDM, 2) proton beam kicking, 3) spallation target development, 4) SD$_2$ properties and preparation, 5) technology of large UCN storage volumes. We expect to have resolved all major physics and technology issues within a year’s time. Assuming full funding at this point makes it feasible to have the UCN source by 2004. The EDM experiment will be installed shortly thereafter.

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