The Ion Background in the Radiative Neutron Decay Experiment

Khafizov R.U.[a], Kolesnikov I.A.[a], Nikolenko M.V.[a], Tarnovitsky S.A.[a], Tolokonnikov S.V.[a], Torokhov V.D.[a], Trifonov G.M.[a], Solovei V.A.[a], Kolkhidashvili M.R.[a], Konorov I.V.[b]

[a]*NRC «Kurchatov Institute», Russia*
[b]*Technical University of Munich, Munich, Germany*

khafizov_ru@nrcki.ru

Annotation

This report aims to research the influence of the ionic background on registration of radiative neutron decay events and the measurement of its branching ratio (B.R.). Our methodology is focused on measuring the spectra of triple coincidences of radiative gamma-quantum, beta electron, and recoil proton and double coincidences of beta electron and recoil proton. The peak on the spectrum of triple coincidences shows the number of radiative neutron decays, while the peak on the spectrum of double coincidences shows the number of regular neutron beta-decays. This methodology enabled us to become the first team to measure the branching ratio of radiative neutron decay B.R. = $(3.2 \pm 1.6)\cdot 10^{-3}$ (where C.L. = 99.7% and gamma quanta energy exceeds 35 keV) in 2005 on our old experimental equipment.

We have now prepared a new experiment on radiative neutron decay with the aim of measuring B.R. with a high degree of precision. The precision of branching ratio measurement is determined using the value of the ion background. The spectrum of double coincidences obtained in our experiment shows a fairly significant ion background, the fluctuations of which indicate the precision of measurement for the number of recoil protons. Because the ion background specifically is quite significant, it appears even under super deep vacuum as beta electrons ionize the highly rarified air inside the chamber. The value of ion background very slowly decreases with decreasing density of air inside the equipment. For example, our experimental data lead to the conclusion that the value of the ionic background is significant when compared with the value of the proton peak and on the other hand decreases only by 5–6 times if the pressure within the chamber goes down by two orders of magnitude. Besides, we discovered an additional wide peak on the spectrum of triple coincidences. This peak consists of delayed gamma quanta created during the ionization of rare gas by beta-electrons.

Thus, this experiment allows us to study another important phenomenon, the ionization of rarified gas by beta electrons with emission of gamma quanta. Our last experiment showed that these two phenomena, radiative neutron decay and ionization with gamma quanta emission, are distinguishable in the case of high time resolution and can be studied separately. This is another important result of our last experiment and in this report we mention that the authors of articles registered namely the ionization with gamma radiation events.

This report is dedicated to a discussion of the computer experiment we conducted using the well-known GEANT4 software package. As a result of these calculations, we demonstrated that the value of the ionic background is proportional to the cubic root of the rarefied air density within the equipment, i.e. it changes very smoothly in relation to the pressure within the chamber. Besides, the report presents a comparison of our measurements of double coincidences and triple coincidences, with two other experimental groups.

Introduction

Presently, the characteristics of the ordinary decay mode are measured with precision of tenths of a percentage point. Under these circumstances, the experimental data obtained by different groups of experimentalists can be reconciled only by taking into account the corrections calculated within the framework of the standard theory of electroweak interactions. This means that the experimental research of the ordinary mode of neutron decay have exhausted their usefulness for testing the standard model. To test the theory of electroweak interaction independently, it is necessary to move from the research of the ordinary branch of decay to the next step, namely, to the experimental research of the radiative decay branch.

The radiative decay branch of elementary particles, where an additional particle, a radiative gamma quantum is formed along with the regular decay products, has been discovered for practically all elementary particles. This has been facilitated by the fact that among the rare decay branches the radiative branch is the most intensive, as its value is proportional to the fine structure constant α and is only several percent of the intensity of the regular decay mode (in other words, the relative intensity B.R. of the radiative decay branch has the value of several hundredths of a unit.)

However, for the neutron this decay branch had not been discovered until recently and considered theoretically only [1–4]. Our first attempt to register the radiative neutron decay events was made on intensive cold neutron beam at ILL [5]. But our experiment conducted in 2005 at the FRMII reactor of Munich Technical University became the first experiment to observe this elementary process [6]. We initially identified the events of radiative neutron decay by the triple coincidence, when along with the two regular particles, beta electron and recoil proton, we registered an additional particle, the radiative gamma quantum

$$n \rightarrow p + e^{-} + \nu + \gamma,$$

and so could measure the relative intensity of the radiative branch of neutron decay B.R.= $(3.2 \pm 1.6)\cdot 10^{-3}$ (with C.L.= 99.7% and gamma quanta energy over 35 keV; before this experiment we had measured only the upper limit on B.R. at ILL [5]).

The main characteristic of any rare mode of elementary particle decay is its relative intensity, branching ratio (BR). By definition, BR is equal to the ratio between the intensity of the rare decay mode and the intensity of the ordinary mode. In the case of neutron, this intensity ratio can be reduced to the ratio between the number of triple coincidences between the registration of beta-electrons, radiative gamma-quantum and the delayed proton N_T to the number of double coincidences between the registration of the ordinary decay products, beta electron and recoil proton N_D:

$$BR = I(\text{radiative decay}) / I(\text{ordinary decay}) = N(e,p,\gamma) / N(e,p) = N_T / N_D.$$

These two values can be determined only from the analysis of double and triple coincidences spectra, which form corresponding peaks. Identifying these peaks and distinguishing them from the significant background is the central problem in the methodology of BR measurements for neutron radiative decay.

Further, this experimental BR value needs to be compared with the theoretical value, estimated within the framework of the electroweak model. Any difference between these two values would mean that we are observing a deviation from the electroweak interaction theory.

Our group calculated the neutron radiative spectrum in the framework of standard electroweak theory in the following papers [1–4]. The calculated branching ratio for this decay mode as a function of the gamma energy threshold was published in these papers. BR value for the energy region over 35 keV was calculated to be about $2.1 \cdot 10^{-3}$.

It follows that to measure the main characteristic of radiative neutron decay it is necessary to obtain and analyze the spectra of double and triple coincidences. So, it is necessary to consider the main particularity of these spectra – the ion and gamma backgrounds.

Let us consider in detail the question around the value of ion background in the experiment on radiative neutron decay, namely, its value in the spectrum of double coincidences of electron and proton. Theory makes it clear that the number of ions created by an electron that spreads in the media of its path with length of L is equal to $N_{ion} = L/\lambda$. Here, λ is the length of the electron's free path in media with molecular density n. If ionization cross section of media is σ_i, then the length of the free path is inversely proportional to the product of media density to the cross section $\lambda = (n\sigma_i)^{-1}$. On the other hand, if the probability of the one media atom ionizatin is $P(n)$, then the number of ions N_{ion} created when the electron cross the media equals the product of this probability to the total number N of atoms on the electron trajectory length L. This number is equal to the ratio of the trajectory length L to the average distance between nearest atoms of media $\ell = n^{-1/3}$ with density n: $N = L/\ell$. Thus, we arrive at the following chain of equations:

$$N_{ion} = \frac{L}{\lambda} = Ln\sigma_i = P(n)N = P(n)\frac{L}{l} = P(n)Ln^{1/3}.$$

Thus, the classic probability of ion creation per one media atom with density n is equal to the ratio between the two areas – that of ionization cross section σ_i to area $S = n^{-2/3}$, the area per one media atom: $P(n) = \sigma_i/S = \sigma_i \cdot n^{2/3}$.

This formula occurs in the simplest model of a "perfectly black sphere". Introducing a random value, aim distance ρ, leads to the probability of ionization dependent on that aim distance of $P(\rho) = 1$ for all aim distances shorter than the atom radius $a = (\sigma_i/\pi)^{1/2}$ while for greater aim distances probability of ionization is 0 (see Fig. 1).

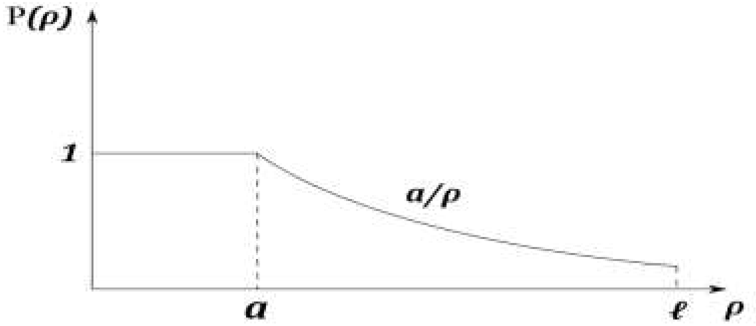

Fig.1. The dependence of the ionization probability on ρ. For the usual model: $P(\rho) = 1$ for $\rho < a$ and $P(\rho) = 0$ for $a < \rho < \ell$; for Coulomb interaction model $P(\rho) = 1$ and $P(\rho) = a/\rho$ for $a < \rho < \ell$.

However, in the case of ionization process in highly rarefied media this simple model becomes inaccurate as it does not take into account Coulomb interaction, which may have a fairly long "Coulomb tail" inversely proportional to the aim distance. In this case, one must consider a more realistic model where probability $P(\rho)$ is not zero, when the electron flies by the atom without touching it, i.e. at aim distances ρ greater than a. So, it is necessary to consider the long "Coulomb tail" of distribution P(ρ), which falls inversely proportionally to the aim distance (see Fig. 1). Thus, the total ionization cross section will depend on density and have an additional term, inversely proportional to the cubic root of media density n:

$$\sigma_{tot} = \int_0^{2\pi} d\varphi \int_0^{a} \rho d\rho + \int_0^{2\pi} d\varphi \int_a^{l} \frac{a}{\rho} \rho d\rho = \pi a^2 + 2\pi a(l-a) = -\pi a^2 + 2\pi a l = -\sigma_i + 2(\pi\sigma_i)^{1/2} n^{-1/3}$$

The probability of ionization per one atom will be: $P(n) = \sigma_{tot} \cdot n^{2/3} = -\sigma_i \cdot n^{2/3} + 2(\pi\sigma_i)^{1/2} \cdot n^{1/3}$.

It is evident that in extremely rarified media where $\sigma_i \cdot n^{2/3}$ is significantly below 1, the second member of this formula leads and significantly exceeds the first. Thus, probability of ionization of one atom becomes proportional to the cubic root of density (pressure), i.e. depends on density in a very smooth way. This, in turn, leads to a gradual reducing of the ion background dependency on density and this background cannot be ignored even in highly rarified media. For example, a fall in pressure within the experimental setup of two orders of magnitude leads to a fall in the ionic background equal to the cubic root of pressure, i.e. 4–5 times. Our experiment observed exactly this behavior of ionic background and, as we'll show later in this report, such smooth dependency on density is experimentally demonstrated when measuring spectra of double coincidences obtained by our and emiT groups.

Analysis and comparison of double coincidences spectra

Here let's pause to analyze the spectra of double coincidences between beta-electron and recoil proton, and compare our spectrum with the results obtained by other authors. We have published the diagram of our experimental equipment in the past [5–6, 8]. Here we will simply note that in its sizes our equipment is comparable to the equipment used by the two other groups and the distance between the observed decay zone and the proton detector in our equipment is about 0.5m. The accelerating potential of the electric field is also approximately the same in all three equipment sets, so all three experiments should lead to similarly forms of double and triple coincidences spectra.

Fig.2 demonstrates the summary statistics on double e-p coincidences (coincidences of electron with delayed proton). Fig.2 clearly shows two major peaks: one peak with a maximum in channels 99–100, which is the peak of zero or prompt coincidences [6, 8]. The position of this peak marks the zero time count, namely the time when the electron detector registered the electron. This peak is not physics-related in its nature. Instead, it is a reaction of the detectors and the electronic system to the registration of the beta electron. It is namely the pulse from the electron channel that opens the time windows on spectra Fig.2 for 2.5 μs forward and backwards. The next peak visible in Fig.2 has a maximum in channel 120 and is the peak of e-p coincidences of beta-electron with delayed proton.

An analogous situation was observed in experiments on the measurement of the correlation coefficients by two independent groups at ILL [10] and emiT group at NIST [11], and it was also mentioned at [12]. We would especially like to emphasize the correspondence of our spectrum of double coincidences with an analogous spectrum from the result obtained by the emiT group from NIST [11]. In Fig.3 we present their spectrum and diagram for the registration of the beta electron and the recoil proton. A comparison of our results with the results of the emiT group shows their unquestionable similarity. Moreover, the position of the second proton peak in Fig.3 (emiT group), like in Fig.2 (our result), corresponds well to the simple estimate obtained by dividing the length of a proton trajectory by its average speed.

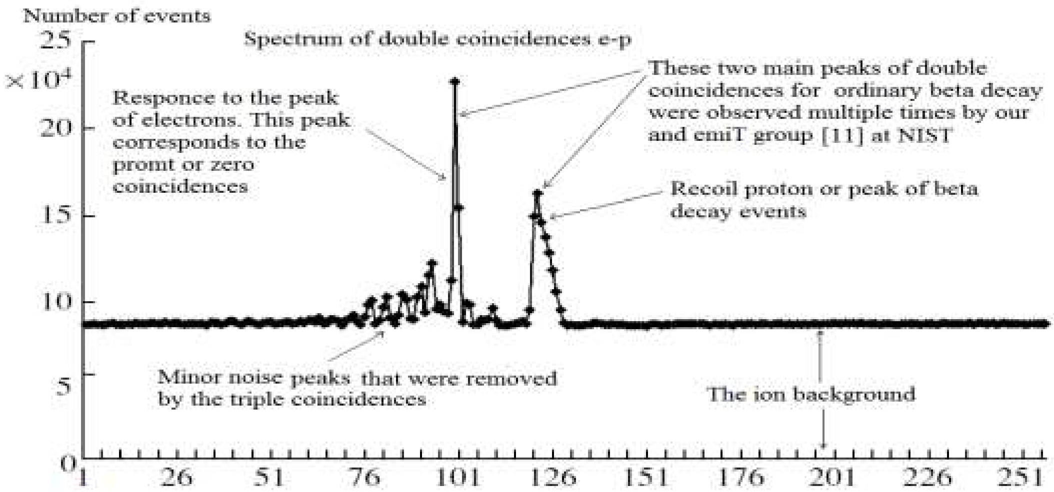

Fig.2. Timing spectrum for e-p coincidences. Each channel corresponds to 25 ns. The peak at channel 99–100 corresponds to the prompt (or zero) coincidences. The coincidences between the decay electrons and delayed recoil protons (e-p coincidences) are contained in the large peak centered at channel 120.

Here we will also note the presence of a significant homogenous ionic background in Fig.2 and Fig.3. However, in both cases this background allows to easily distinguish the neutron decay peak. As we will shortly demonstrate, this ionic background will play a dominant role in the presence of a strong magnetic field and it will become impossible to distinguish events of ordinary neutron decay against it.

Following Avogadro's law, even in the case of a very deep vacuum under pressure of 10^{-6}–10^{-8} mbar, air molecule concentration remains very high. In fact, it is sufficient for beta-electrons produced in neutron decay to create a significantly high ionic background. Here one must note that the probability of ion creation along the trajectory of beta-electron in inverse proportion to the average distance between neighboring ions, i.e. proportional not to the molecule concentration but to the cubic root of this value. From this observation it follows that the value of the ionic background does not significantly depend on the vacuum conditions inside the experimental chamber. In our case, pressure was two orders of magnitude greater than the pressure in the emiT experiment. However, we observed an ionic background of only 4–5 times their background. This estimate is confirmed when one compares the spectra in Fig.2 and Fig.3. Our spectrum, presented in Fig.2, has a 1:1 ratio of the value of e-p coincidences peak and the value of the background. The emiT group (Fig.3) spectrum has a ratio of 4:1 – 5:1, i.e. only 4–5 times our number, that is equal to the cubic root of pressure ratio in both teams' work (see Introduction).

We will present the specific calculations using the GEANT4 package in a separate paper, where we will consider the ionization process in more detail. It is noteworthy that in our case it is impossible to isolate and track individual tracks of electrons ionizing the residual air in the chamber due to their multiple reflections and scattering on the walls of the chamber, the neutron guide and other structural elements of the installation. As shown by concrete calculations, in this case it makes more sense to talk about the steady-state electron density ρe inside the chamber and, accordingly, the ion density ρ_i. The density of ions ρ_i is proportional to the density of electrons ρ_e, with the proportionality factor being the probability of the formation of the ion $P(\mathrm{n})$ (see Introduction): $\rho_i = P(\mathrm{n})\cdot\rho_e = 2(\pi\sigma_i)^{1/2}\cdot n^{1/3}\rho_e$. Thus, the ratio of the ionic background value to the proton peak value also decreases in proportion to the cube root of density or pressure.

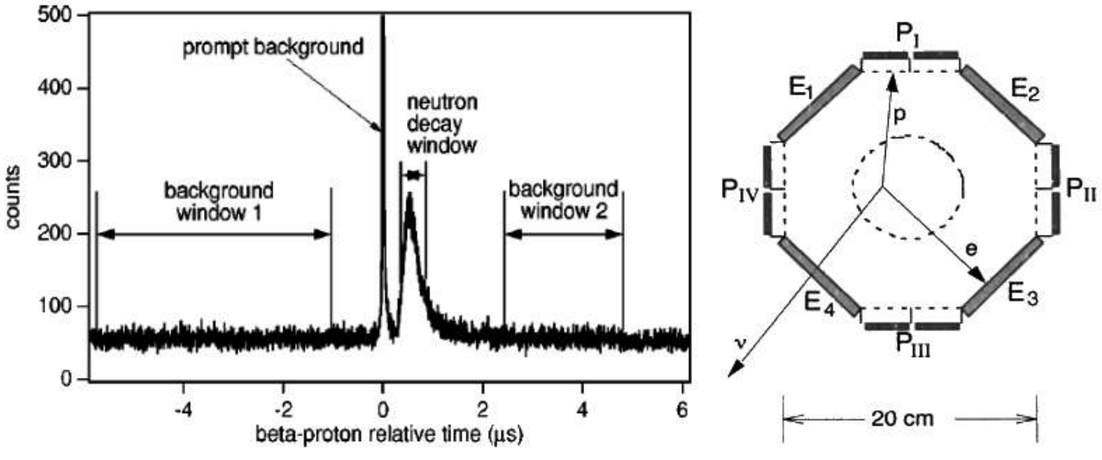

Fig.3. Spectrum of double electron-proton coincidences obtained by emiT Group [11] with two peaks and ion background value comparable to the neutron decay peak; emiT group scheme for registering beta electron and recoil proton.

Fig.2 shows that the total number of events in e-p coincidences peak in our experiment equals $N_D = 3.75\cdot10^5$. This value exceeds the value we obtained in our previous experiment conducted on beam PF1 at ILL by two orders of magnitude. It was precisely because of the low statistics volume that we could not identify the events of radiative neutron decay in that experiment and instead defined only the upper B.R. limit [5]. It is very important to note that the peak of double coincidences between electron and the delayed proton is observed against a non-homogenous background (see Fig.2 and Fig.3): besides the homogenous ionic background, which has a value comparable to the value of the e-p coincidences peak, there is an obvious peak in channels 99–100. In essence, this peak is a response peak to the time spectrum of electron registration, which contains just one peak in channels 99–100, signifying the time when the electron detector registered the electron. We will shortly see that the radiative peak of triple coincidences appears against a non-homogenous background with not one, but two response peaks.

The remaining peaks in Fig.2 are small, with just seven peaks distinct from the statistical fluctuations. These occurred because of the noise in the electric circuits of the FRMII neutron guide hall. There are no other physics-related reasons for their occurrence. These peaks appeared and disappeared depending on the time of day, reaching their maxima during the work day and disappearing over the weekends. Such behavior was observed throughout the experiment as we collected statistics. Since the nature of these seven small peaks is in no way related to radiative and ordinary decay, we did not emphasize them in our article.

The comparison conducted demonstrates that the spectra of double coincidences obtained in our experiment completely correspond with the results obtained by the emiT group. Now we will compare these two spectra with the spectrum of double coincidences obtained by the third group. Unfortunately, the authors did not publish the spectrum of double coincidences in their original article [7], instead it was only published this year in paper [13].

Fig.4 displays the spectrum of double coincidences and the diagram of their experimental equipment.

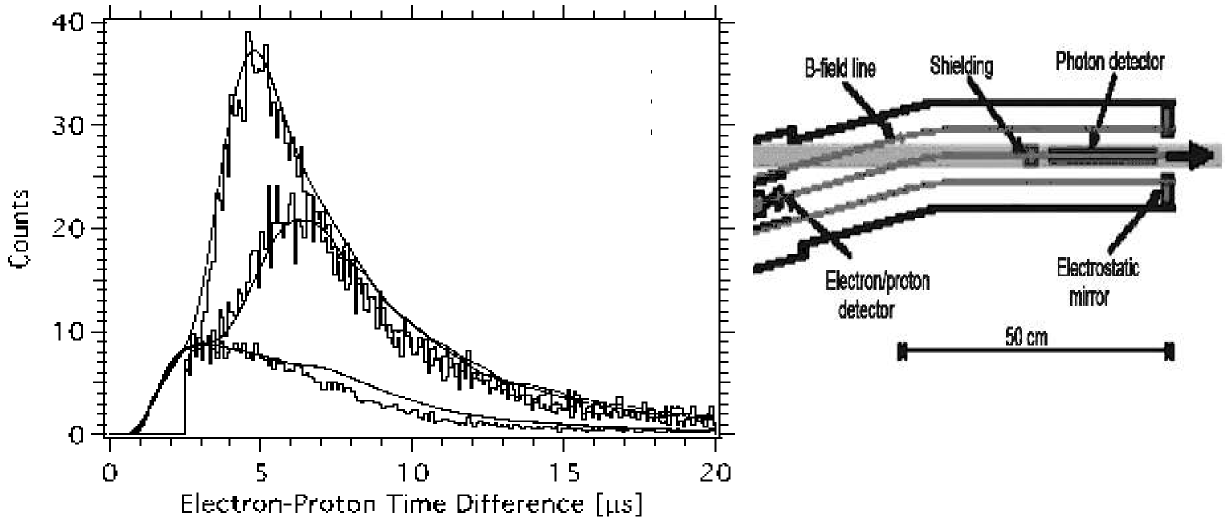

Fig.4. Equipment diagram and the single peak of "electron-proton" coincidences, published in [13]. The lower curve corresponds to 0 volts, the middle curve corresponds to 300 volts and the highest curve corresponds to 500 volts in an electrostatic mirror. The location of the peak's maximum and its significant width differ from our and the emiT results subsequently by one and two orders of magnitude. The location and the width of the peak also deviate by one and two orders of magnitude from the elementary estimates of delay times (see below).

The significant deviation obtained is explained by the fact that the peak in the NIST experiment consists not of beta-decay protons, but rather of ions. The density of gas molecules inside the equipment is proportional to pressure and according to the Avogadro's Law is at the order of 10^7 mol/cm^3 even at the pressure of 10^{-8}–10^{-9} mbar. This is a very significant number, which quite enough for creation the large ionic background in the presence of ionizing radiation. The energy of beta-electrons significantly exceeds the energy of ionization. Besides, the probability of ion creation by electrons is inverse proportional not to volume taken up by one molecule but to the average distance between molecules. It is precisely due to this reason that the ionic background falls proportionally to the cubic root of the pressure and not proportionally to pressure. In the emiT group experiment the pressure was the same as in the NIST experiment, i. so, the ionic background should be the same too. The light ions, together with the beta protons, should have a delay time comparable to 1 μs. The pulses from these particles are simply not visible in the spectrum due to the NIST group's use of combined electron-proton detector (see Figure 5 with the shape of electron and ion pulses). The maximum of the "proton" peak in the NIST experiment, according to the delay times estimations (delay time is proportional to square root of ion mass), falls exactly to the air ions 4–6 μs.

Fig.5 presents the pulse forms on the electron-proton detector. As was pointed out above, the significantly delayed pulses of low amplitude correspond to ion pulses, and the pulses from protons are simply invisible due to a presence of a wide electron pulse of high amplitude. Namely this fact explains the dead zone around zero on the spectrum of electron-ion coincidences in Fig.4.

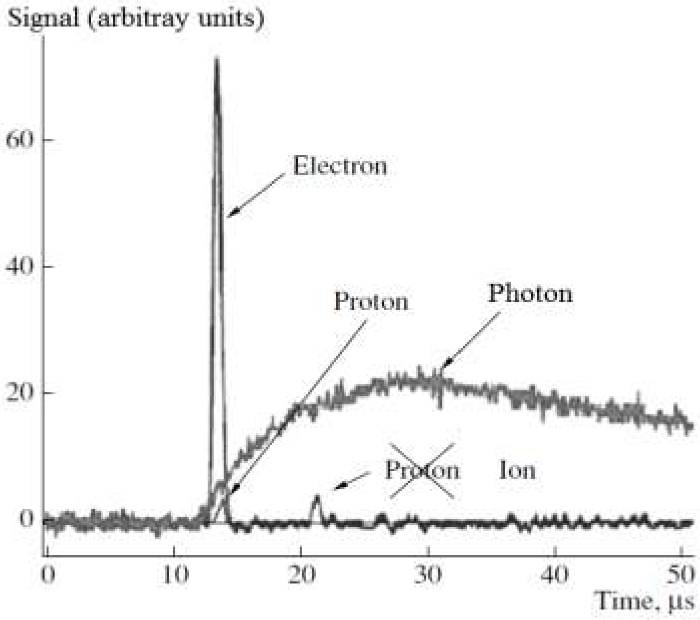

Fig.5. The signal from the decay proton has to be delayed by less than one microsecond, which is why it is located at the base of the electron pulse (see line number 2) and so cannot be registered by the combined electron-proton detector. The pulses that are delayed by longer than 1 microsecond are pulses not from decay protons, as it was indicated in ref. [7], but rather from ions, formed in the decay zone. The line number 1 shows the shape of pulses from the gamma detector.

Analysis and comparison of triple coincidences spectra

In paper [11] the emiT group researched only the ordinary decay mode, thus this comparison is limited to our spectrum of triple coincidences, presented in Fig.5, and the only peak published by the NIST authors in Nature [7], presented in Fig.7. Analysing the double coincidences spectra obtained by our and the emiT groups (both of which present two main peaks) shows that in the spectrum of triple coincidences we should observe not two but three peaks. Namely, along with the sought after radiative peak, the triple e-p-gamma coincidences spectrum should show two (not one!) response peaks to the registration of beta-electrons and the registration of protons. Fig.5 of triple coincidences clearly shows three peaks, and the leftmost peak with the maximum in channel 103 is connected to the peak of the radiative gamma-quanta in question, as this gamma-quantum is registered by the gamma detectors in our equipment before the electron.

It is also important to note that while both teams' double coincidences spectra show the peaks at a distance from each other and easily distinguishable, in the spectrum of the triple coincidences the radiative peak is on the left slope of the response peak to electron registration. This means that we observe the peak of radioactive neutron decay events against a heterogeneous background. At the same time, both response peaks on the spectrum of triple coincidences are significantly wider and located closer to each other than in the original spectrum of double coincidences. As we demonstrate below, one must take into account such spectrum behavior (related to the presence of a response in the electron detector system of data collection) by introducing the non-local response function. Using this well-known method it is possible to distinguish N_T the number of triple coincidences from the heterogeneous background, arriving at the experimental BR value.

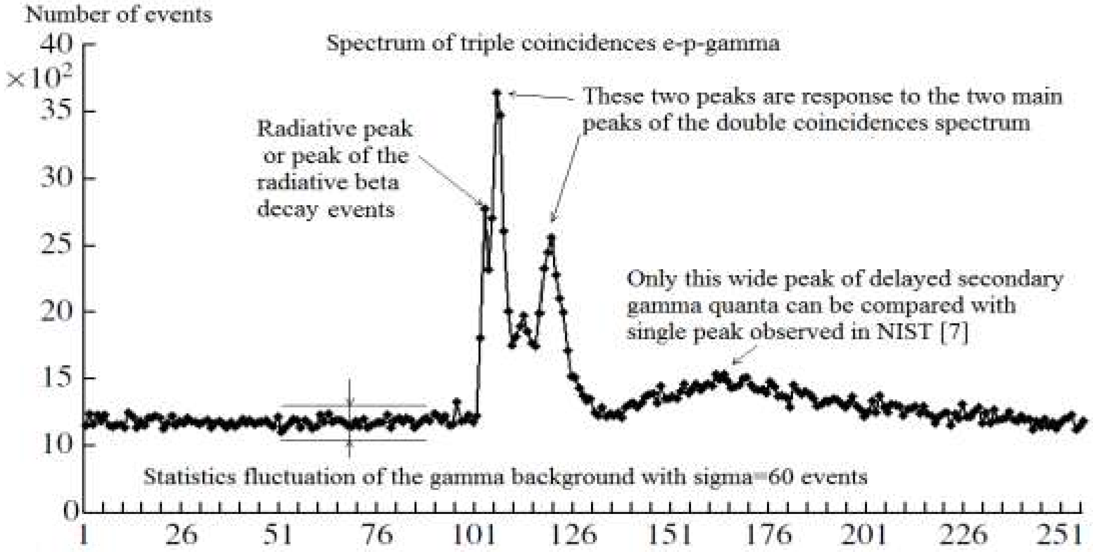

Fig.6. Timing spectrum for triple e-p-g coincidences. Each channel corresponds to 25 ns. In this spectrum, three main peaks in channels 103, 106 and 120 can be distinguished. The leftmost peak in 103 channel among these three main peaks is connected with the peak of radiative decay events.

Comparing Fig.2 and Fig.6, it becomes clear that if we ignore the first leftmost peak with the maximum in channel 103 in Fig. 6, the spectrum of double e-p coincidences will resemble the spectrum of triple e-p-γ coincidences in Fig.2. The peak with the maximum in channel 106 in Fig.6 is connected to the left peak of false coincidences in Fig.2, and the peak with the maximum in channel 120 in Fig.6 is connected to the right peak of e-p coincidences in Fig.2. The emerging picture becomes obvious when one uses a standard procedure, introducing a response function for gamma channel $R_\gamma(t,t')$ [6] , which is also necessary for calculating the number of triple radiative coincidences N_T in radiative peak:

$$S_{out}(t)=\int S_{in}(t')R_\gamma(t,t')dt'$$

Using the method of response function, one can confidently define our double-humped background: the narrow peak with the maximum in channel 106 in Fig.6 is the response to the narrow peak of zero coincidences (by other words this peak is response to beta-electron registration) in channels 99–100 in Fig.2, and the second peak in this double-humped background in Fig.5 is the response to the peak in channels 117–127 in Fig.2 (or this peak is response to proton registration).

It must be noted that in our case we have to use the non-local response function, as the peaks on the original spectrum $S_{in}(t)$ of double coincidences are significantly narrower than those in the spectrum $S_{out}(t)$ of triple coincidences and also are shifted in their relative positions. In this case we use “functional” multiplication, however if we use the local response function, the triple coincidences spectrum is arrived at by simple multiplying the double coincidences spectrum by a number, in which case neither the width of the peaks nor their position change. It is also evident that the local response function approach leads to an erroneous number of triple coincidences N_T and, therefore, the wrong BR value.

When discussing the similarities between the spectra in Fig.2 and Fig.6, it is important to note that the response peak in Fig.6 with a maximum in channel 106 is shifted to the right or delayed in comparison to the peak responding to electron registration in channel 100 in Fig.1. This is due to the fact that in our electron diagram we used a constant fraction discriminator (CFD). CFD has its own delay line and the location of the time-pickoff signal it generates is determined by the method of comparing the fraction of the original signal to the delayed (CFD method [14]). Thus, there is a shift in the first response peak with a maximum in channel 106 in Fig.6 versus the first peak in Fig.2 with the maximum in channel 100. The value of this delay is equal to the front duration of the gamma quantum signal and is on average 150 ns. The CFD method obviously also shifts the radiative peak, but it should be located to the left of the response peak, as is observed in Fig.6.

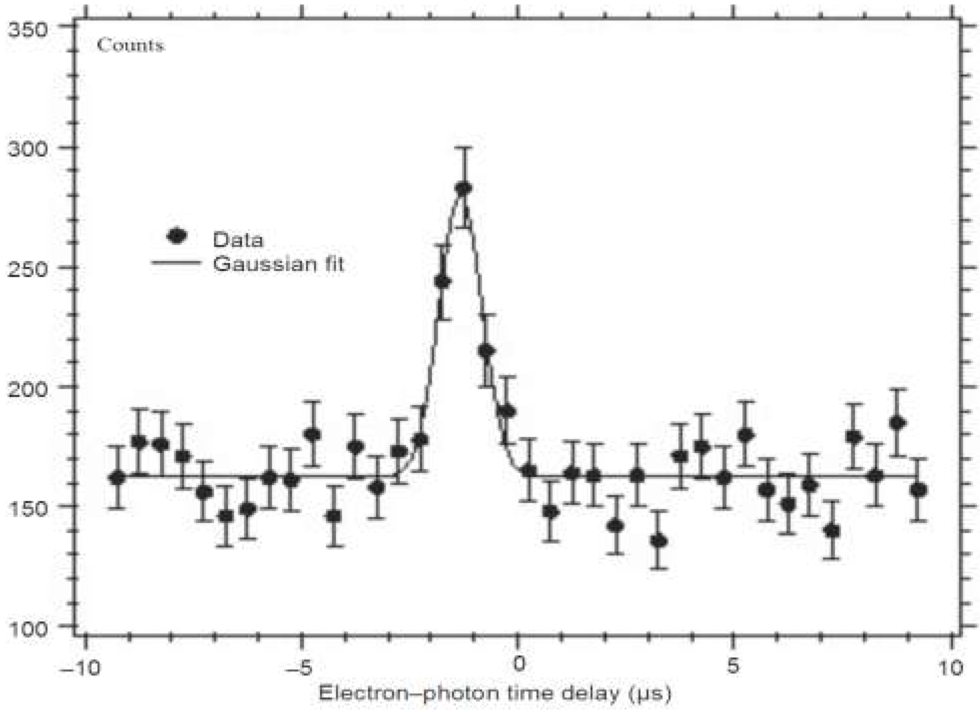

Fig.7. Only peak of "electron-photon" coincidences, shifted to the left of 0 – the time of beta-electron registration – by 1.25 microseconds, published in [7, 11].

As for the wide, almost indistinguishable peak in channel 165 in Fig.6, its influence on the radiative peak in channel 103 is negligible. Its nature is in no way related to the researched phenomenon, so we do not discuss it in our article. This peak is created by the radioactive gamma quanta delayed on average by 1.25 μs and emitted by the radioactive medium within our experimental equipment. The medium is activated by registered beta-electrons. This event of artificial, induced radioactivity has been known for over 100 years and does not have anything in common with the new event of radiative neutron decay which is the subject of current research. As we will demonstrate below, only this 1 microsecond peak and delayed from the registration time by about the same time can be compared to the peak observed by the authors of paper [7] at NIST (see Fig.7). Thus, the authors of this experiment observed not the events of radiative decay but rather the event of artificial radioactivity, already well known in the time of Joliot-Curie.

After analyzing the spectra with the help of the non-local response function $R_\gamma(t,t')$ we finalize the average value for the number of radiative neutron decays N_T =360 with a statistics fluctuation of 60 events. B.R. can be expressed as a ratio of N_T to N_D as BR = k (N_T/N_D), where coefficient k = 3.3 is the geometrical factor that we can calculate by using anisotropic emission of radiative gamma-quanta [4]. With the number of observed double e-p coincidences $N_D = 3.75\cdot 10^5$ and triple e-p-γ coincidences N_T = 360, one can deduce the value for radiative decay branching ratio of $(3.2 \pm 1.6)\cdot 10^{-3}$ (99.7 % C.L.) with the threshold gamma energy ω = 35 keV. The average B.R. value we obtained deviates from the standard model, but because of the presence of a significant error (50%) we cannot make any definite conclusions. The measurements must be made with greater precision. According to our estimates, in the future experiment we will be able to make more definite conclusions about deviation from the standard electroweak theory with experimental error less than 10%.

The difference between the NIST experiment and our experiment becomes immediately apparent. First and foremost, it is the time scale: in our spectra, the scale is measured in nanoseconds, while in the other experiment the scale is in microseconds. Besides, we used three types of detectors, each of which registered its own particle: one detector for the electrons, one for the protons, and six identical detectors for the radiative gamma-quanta (see [6]). The duration of the front pulse from the electron and proton detectors is 10 nanoseconds in our experiment and 100 times greater than that in the NIST experiment, in the order of 1 μs. The rise time of gamma signal from our gamma-detectors is on average 150 ns, and from avalanche diode on the NIST equipment greater than 10 μs, besides that the diode pulse arrives with significant noise, which makes the thickness of the front pulse line equal to more than 0.5 μs (see the photon line in Fig.7 from [7]). All of this leads to our factual time resolution being two orders of magnitude better than the resolution achieved in the NIST experiment. However, as the two experiments used equipment which was practically the same in size and smaller than 1 meter, the choice of the time scale is a matter of principle. Given this geometry, it is impossible to get microsecond signal delays from all of the registered charged particles, i.e. electrons and protons. In this light, it is surprising that the peak identified by the authors of the NIST report [7] as the peak of radiative gamma-quanta, is shifted by 1.25 microseconds to the left. The expectation that magnetic fields of several tesla in magnitude delay all electrons and protons, are absolutely ungrounded.

Indeed, the magnetic field cannot change the speed of charged particles. It can only twist a line trajectory into a spiral. The length l of this spiral depends on angle θ between particle velocity and magnetic field direction. In beta decay, electrons can fly out under any angle θ, therefore the magnetic field can increase the time of delay by several orders of magnitude only for a negligible portion of the charged particles. Even this negligible number of particles that flew out at an almost 90 degree angle to the direction of the magnetic field that coincides with the direction of the narrow neutron guide (see Fig.4) will most likely end up on the walls of the neutron guide rather than reach and hit the detector due to the presence of the strong electrostatic field. Because the distance between the point of decay and the detector is about 0.5 meter and electron velocity is comparable with speed of light, the electron time of delay should be less than a microsecond by two orders of magnitude.

Thus, both the 1 microsecond shift and the width of the only peak in Fig.7 in the experiment conducted at NIST, is in sharp contradiction to elementary estimates. We, on the other hand, did not observe any wide peaks before electron registration and our gamma background is very even in this part of the spectrum (see Fig.6). However, when we assume that the NIST experiment authors observed the wide peak, shifted by 1 microsecond, not before, but after the registration of beta-electrons. In that case, the wide peak on our spectrum in Fig.6 completely corresponds to the wide peak in Fig.7. However, as noted above, density of gas molecules remains high even with the pressure of 10^{-8}–10^{-9} mbar and this residual gas is activated by beta-electrons. The wide peak in our spectrum is formed by the delayed gamma quanta from this induced artificial radioactivity.

Conclusions

The main result of our experiment is the discovery of the radiative peak namely in the location and of the width that we expected. The location and the width of the radiative peak correspond to both estimates and the detailed Monte Carlo simulation of the experiment. Thus, we can identify the events of radiative neutron decay and measure its relative intensity, which was found to be equal B.R. = $(3.2 \pm 1.6)\cdot 10^{-3}$ (with C.L.= 99.7% and gamma quanta energy over 35 keV).

At the same time, the average experimental B.R. value exceeds the theoretical value by 1.5 times. However, due to a significant error we cannot use this result to assert that we observe a deviation from the standard model. Therefore, our most immediate goal is to increase experiment precision, which we can improve by several percent according to estimates.

For last two years we were preparing this new experiment and conducted number of tests for our new electronics. We constructed multichannel generator what can generate the pulses with the same forms as our electron, proton and gamma detectors. During these tests we got the same responses as during our last experiment on real neutron beams at FRMII. It means that all additional peaks on our spectra have no any physics reasons and It proves once more that we were absolute correct when applied the response function method for explaining these peaks as response ones and for developing our experimental spectra.

We created and tested our new electronic system for obtaining experimental spectra. By using this new programmable electronics we can significantly reduce the influence of response peaks on peak with radiative decay events. Now we can get this peak almost isolated from responses. On our estimations all these allow us to reach accuracy for our new experiment about 1%. So, on the base of our new electronics we can confirm or refuse the deviation of our average experimental value of BR from the standard model one.

As concerning the comparison of our experimental results with others we can make the following two main conclusions. The main parameters of our spectrum of double electron-proton coincidences identifying the events of ordinary neutron decay fully coincide with an analogous spectrum published by emiT group in [11].

Unfortunately we cannot say same for another experiment measuring the radiative neutron decay published in [7]. Particularly vexing is the authors' unsubstantiated assertion that they observe their only wide peak of gamma quanta before the registration of beta-electrons. Both the position and the width of this peak are located in sharp contradiction to both the elementary estimates, and the results of our experiment. In the course of our entire experiment we did not observe such a wide peak in the triple coincidences spectrum, located before the arrival of electrons at a huge distance of 1.25 μs. However, it is possible to reconcile our spectra of triple coincidences with the one isolated peak observed at NIST if we assume that at NIST, the gamma-quanta were registered after the beta electrons. Only in this case does the NIST peak almost completely coincide with the peak we observed in the spectra of triple coincidences with the maximum in channel 165, both in terms of the huge delay of 1.25 μs and in terms of its huge width. This peak is created by the delayed secondary radioactive gamma-quanta, arising from the activation by beta electrons of the media inside experimental chamber, which was the real object of the NIST experimentalists' observation.

Despite the recent disagreements [15], which we consider to be subjective in nature [16], we acknowledge the contribution of our Western colleagues Profs. N. Severijns, O. Zimmer and Drs. H.-F. Wirth, D. Rich to our experiment conducted in 2005. Here it is important to note that the authors of the article published in Nature [7] consciously misled first our Western colleagues and then the physics community at large by insisting that their only wide peak is removed by 1.25 microseconds to the left from the time of electron registration, when in reality this peak was formed by delayed gamma-quanta, emitted by the activated medium inside the experimental equipment, and corresponds to our wide peak with the maximum in channel 165 (refer to Fig.6) [15, 16]**.** The authors would like to thank Profs. D. Dubbers and Drs. T. Soldner, G. Petzoldt and S. Mironov for valuable remarks and discussions. We are also grateful to the administration of the FRMII, especially Profs. K. Schreckenbach and W. Petry for organizing our work. We would especially like to thank RRC President Academician E.P. Velikhov and Prof. V.P. Martem'yanov for their support, without which we would not have been able to conduct this experiment. Financial support for this work was obtained from RFBR (Project N 014-02-00174).

References

1. Gaponov Yu.V., Khafizov R.U., Phys. Lett. B **379** (1996) 7–12.
2. Yu.V. Gaponov, R.U. Khafizov., Radiative neutron beta-decay and experimental neutron anomaly problem. Weak and electromagnetic interactions in nuclei (WEIN '95): proceedings. Edited by H. Ejiri, T. Kishimoto, T. Sato, River Edge, NJ, World Scientific, 1995, 745p.
3. R.U. Khafizov, N. Severijns, About the possibility of conducting an experiment on radiative neutron beta decay Proceedings of VIII International Seminar on Interaction of Neutrons with Nuclei (ISINN-8) Dubna, May 17–20, 2000 (E3-2000-192), 185–195.
4. Khafizov R.U., Physics of Particles and Nuclei, Letters **108** (2001) 45–53.
5. M. Beck, J. Byrne, R.U. Khafizov, et al., JETP Letters **76**, 332 (2002).
6. R.U. Khafizov, N. Severijns, O. Zimmer, et al., JETP Letters **83**, 5 (2006).
7. J.S. Nico, et al., Nature, v. **444** (2006) p. 1059–1062.
8. R.U. Khafizov, N. Severijns et al., Discovery of the neutron radiative decay Proceedings of XIV International Seminar on Interaction of Neutrons with Nuclei (ISINN-14), Dubna, May 24–25, 2006.
9. B.G. Yerozolimsky, Yu.A. Mostovoi, V.P. Fedunin, et al., Yad. Fiz. **28**, 98 (1978); [Sov. J. Nucl. Phys. **28**, 48 (1978)].
10. I.A. Kuznetsov, A.P. Serebrov, I.V. Stepanenko, et al., Phys. Rev. Lett. **75**,794 (1995).
11. L.J. Lising, S.R. Hwang, J.M. Adams, et al., Phys. Rev. C **6**, 055501 (2000).
12. J. Byrne, R.U. Khafizov, Yu.A. Mostovoi, et al., J. Res. Natl. Inst. Stand. Technol. **110**, 415 (2005).
13. R.L. Cooper, T.E. Chupp, M.S. Dewey, et al, Phys. Rev. C **81**, 035503 (2010).
14. T.J. Paulus, IEEE Transactions on Nuclear Science, v.NS-32, no.3, June, p.1242, 1985.
15. N. Severijns, et al., e-print arXiv:nucl-ex/0607023; J. Nico, private communication.
16. R.U. Khafizov, V.A. Solovei, e-print arXiv:nucl-ex/0608038.