

## Measurement methodology for the main characteristic of radiative neutron decay

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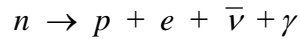
### Annotation

Based on critical analysis of our experiment on radiative decay, as well as the experiment of emit group and work conducted at NIST, we present the methodology for measuring the main characteristic of radiative neutron decay, namely, its relative intensity (B.R.). Relying on spectra measurements of double beta-electron and proton coincidences and triple coincidences of beta-electron and proton with the gamma quantum, we discovered the events of radiative neutron decay and measured its relative intensity  $B.R.=(3.2\pm 1.6)10^{-3}$  (with C.L.=99.7% and gamma quantum energy over 35 keV).

The double coincidences spectrum we measured corresponds in all of its characteristics with an analogous spectrum obtained by emit group studying ordinary beta neutron decay. In particular, this group also observed a significant ionic background, comparable with the value of the beta-decay peak. From Avogadro's law it follows that even with a very deep vacuum inside the vacuum chamber, molecule concentration remains sufficient for the creation of a significant ionic background, comparable to the effect itself. Besides, the value of the ionic background is only very slightly dependent on the vacuum: it is proportional to the cubic root of pressure. Even if the pressure is reduced by two orders of magnitude, the value of the ionic background goes down only by a few times. The analysis of ionic background structure shows that research publication presents not a narrow beta-decay peak but rather a wide ionic peak. Gamma background must also be considered when measuring the triple coincidences. Besides, the gamma spectrum shows a wide peak of artificial radioactivity due to the presence of intense radiation. In its width, the peak corresponds to the only gamma peak measured at NIST and so has no relation to radiative neutron decay. Our spectrum of triple coincidences shows not only this wide peak of artificial radioactivity but also a narrow peak, formed by the events of radiative neutron decay. However, our spectra also show additional background response peaks, arising from the response of our electronic system to the registration of beta-electrons and protons. The only solution to the situation where backgrounds cannot be ignored is precisely measuring the time spectra of double and triple coincidences and clearly distinguishing both the ionic and the gamma backgrounds from these spectra. For our new experiment on precise BR measurements we created a new electronic system, which significantly overcomes the response and which allows to obtain a BR value with 1% precision by measuring the time spectra of double and triple coincidences.

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**Introduction.** Among the many branches of elementary decay with charged particles in the final state, the radiative branch, where the decay occurs with the creation of an additional particle – the gamma quantum, is usually the most intensive, as the relative intensity ( or branching ratio B.R. ) of this mode is determined by the fine structure constant  $\alpha$  of  $10^{-2}$  order of magnitude. This decay branch is well established and has been investigated for almost all elementary particles. However, the radiative decay of the free neutron



has not been discovered, and all the experiments were aimed at the study of the ordinary neutron decay branch.

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 to 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 temporary spectra of double and triple coincidences, which form corresponding peaks. Identifying these peaks and distinguishing them from the significant background is the central problem in the methodology of BR measurements.

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.

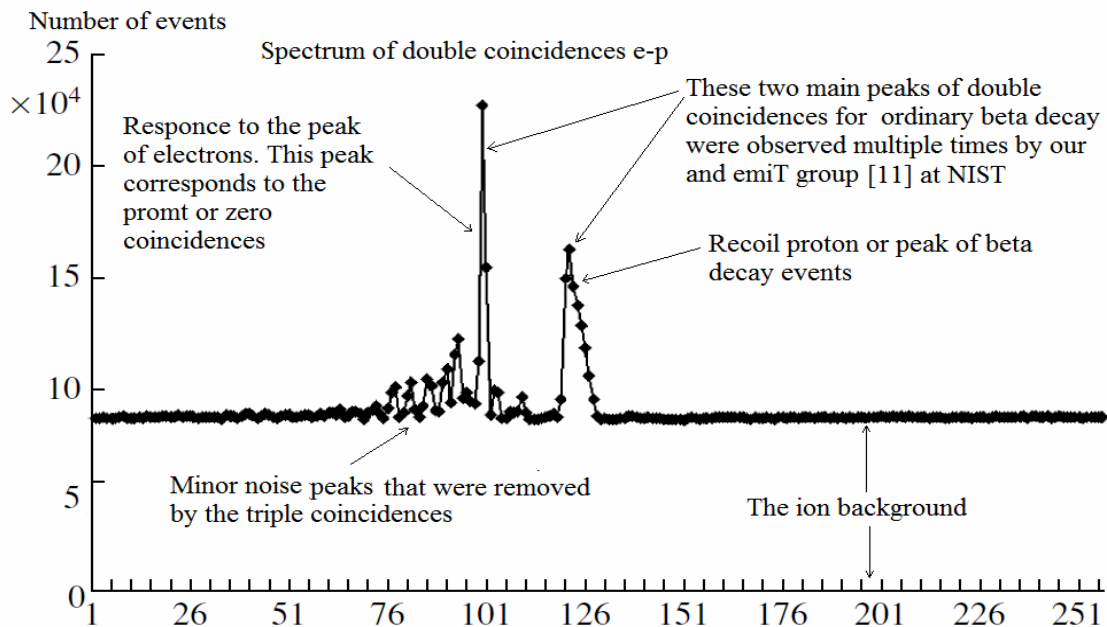
Our group calculated the neutron radiative spectrum in the framework of standard electroweak theory about ten years ago [1-4]. The calculated branching ratio for this decay mode as a function of the gamma energy threshold was published in these papers. This value for the energy region over 35 keV was calculated to be about  $2 \cdot 10^{-3}$ .

In 2002 we conducted the first experiment on the discovery of this rare neutron decay branch on the intensive cold neutron beams at ILL (Grenoble, France), where we received a limit for the relative intensity: B.R.  $< 6.9 \cdot 10^{-3}$  ( 90% C.L.) [5]. This value exceeds the theoretical value we calculated and published by only a few orders of magnitude. This, in turn, means that in our experiment of 2002 we came very close to discovering the radiative mode of neutron decay. For reasons outside of our control we did not receive beam time on intensive cold neutron beam at ILL for a number of years and were able to continue our experiment only in 2005, after we received beam time at the newly opened FRMII reactor in Munchen. In the 2005 experiment we identified the events of radiative neutron decay and measured its relative intensity B.R.  $= (3.2 \pm 1.6) \cdot 10^{-3}$  with C.L. = 99.7% and gamma quanta energy over 35 keV [6]. A year after our discovery of the radiative neutron decay, a NIST experimental group published the results of their experiment on the study of the radiative neutron decay [7] in Nature, with their own value of B.R.  $= (3.13 \pm 0.34) \cdot 10^{-3}$  with C.L. = 68% and gamma quanta energy from 15 to 340 keV. Here it is also important to note the work of the emiT group, where the team researched the asymmetry of electron departure in ordinary neutron decay and measured the time spectrum of double coincidences between beta-electron and the delayed proton.

We will formulate the optimal conditions for our future experiment on radiative neutron decay based on a comparison between the experimental spectra of double and triple coincidences, obtained in the experiments of these three groups.

**Comparison of double coincidences spectra.** We have published the diagram of our experimental equipment on numerous occasions [5-6, 8]. Here we will simply note that in its parameters our equipment is comparable to the equipment used by the two other groups and the distance between the observed decay mode 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 shaped spectra of double and triple coincidences spectra.

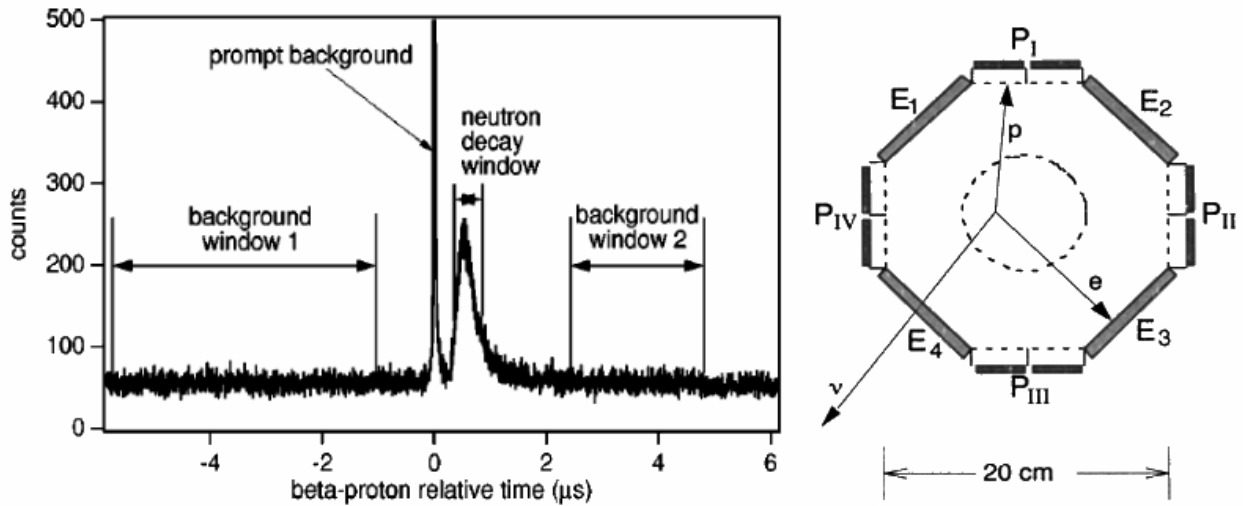
Fig. 1 demonstrates the summary statistics on double e-p coincidences (coincidences of electron with delayed proton). Fig. 1 clearly shows two major peaks: one peak with a maximum in channels 99-100, which is the peak of zero or prompt coincidences [6, 8]. The position of this peak marks the zero time count, namely the time when the electron detector registered the electron. This peak is not physical 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. 1 for 2.5  $\mu$ s forward and backwards. The next peak visible on Fig. 1 has a maximum in channel 120 and is the peak of e-p coincidences of electron with delayed proton.



**Fig. 1.** 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.

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]. On Fig. 2 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. 2 (emiT group), like in Fig. 1 (our result), corresponds well to the simple estimate obtained by dividing the length of a proton trajectory by its average speed.

Here we will also note the presence of a significant homogenous ionic background in Fig. 1 and Fig. 2. 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.



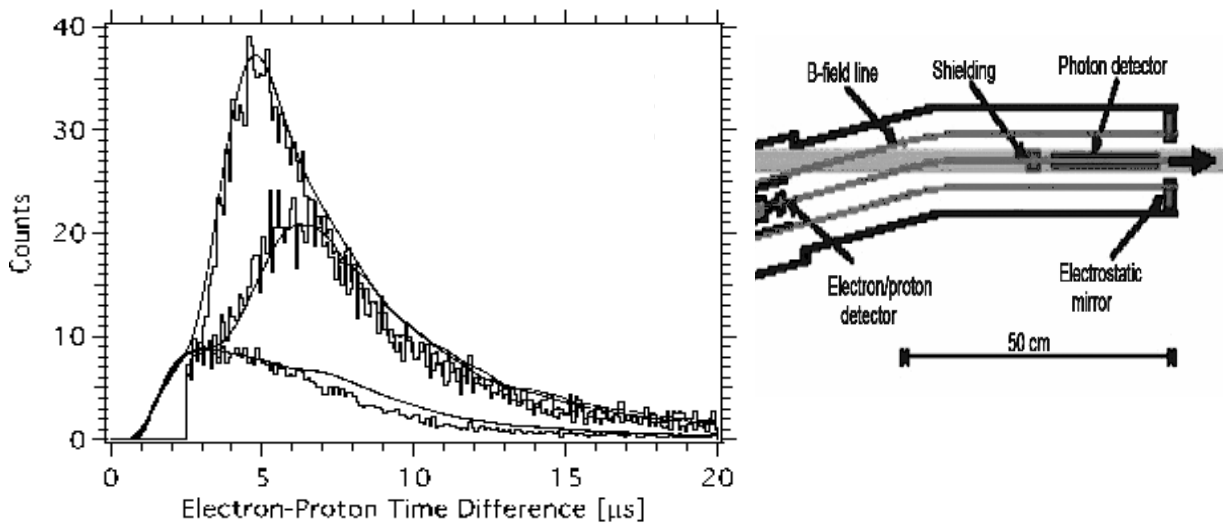
**Fig. 2** Spectrum of double electron-proton coincidences obtained by emiT Group [11] with two peaks and ion background value comparable to the neutron decay peak; emiT group scheme for registering beta electron and recoil proton.

Fig. 1 shows that the total number of events in e-p coincidences peak in our experiment equals  $N_D=3.75 \cdot 10^5$ . 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: 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 on Fig. 1 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 our results on the spectra of double coincidences 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 Nature article, instead it was only published this year in paper [13]. Fig 3 displays the spectrum of triple coincidences and the diagram of their experimental equipment.

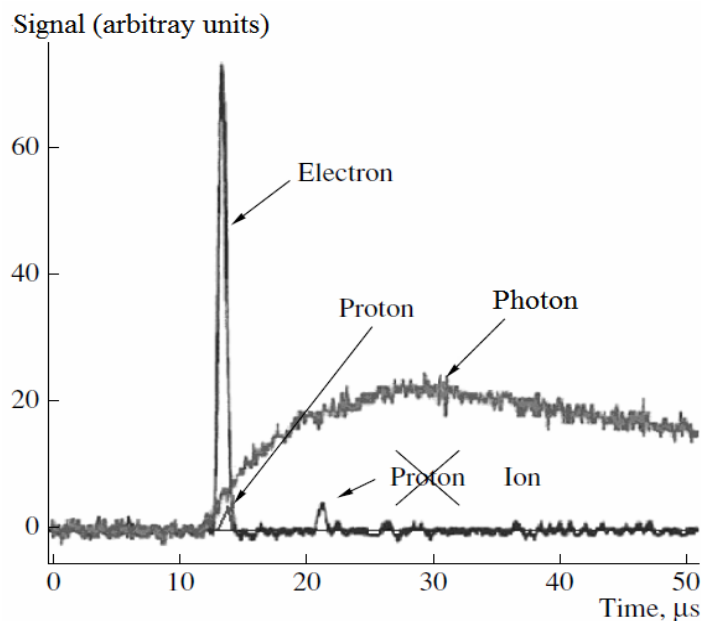


**Fig. 3** Equipment diagram and the single peak of “electron-proton” coincidences, published in [13]. The location of the peak’s maximum and its significant width differ from our and the emiT results subsequently by one and two orders of magnitude. The location and the width of the peak also deviate 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<sup>3</sup> 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 proportional not to

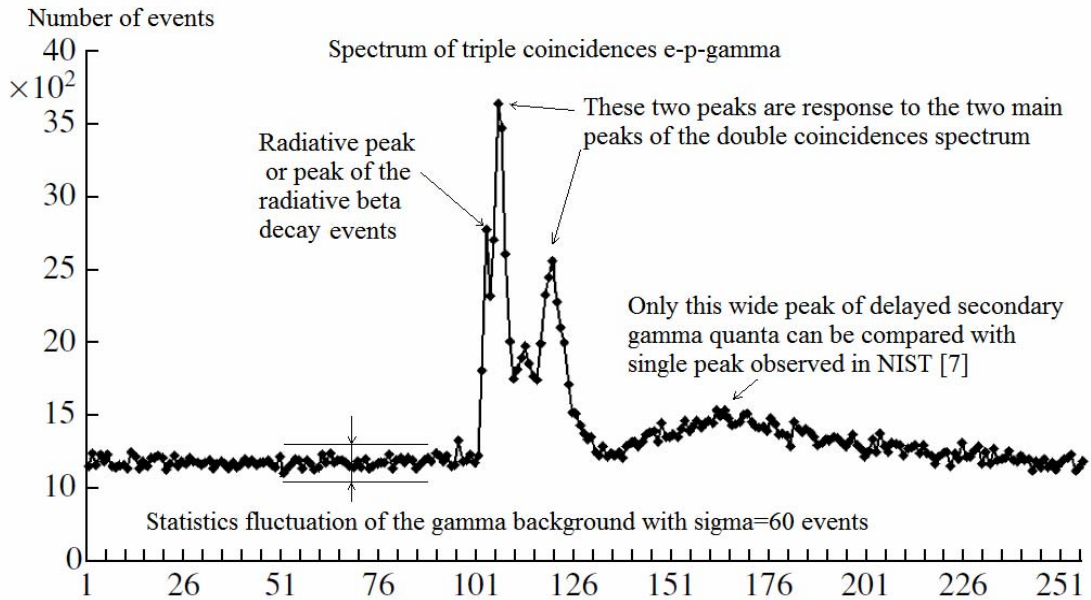
volume taken up by one molecule but to the average distance between molecules. It is precisely due to this reason that the ionic background falls proportionally to the cubic root of the pressure and not proportionally to pressure. In our experiment the pressure was  $10^{-6}$  mbar, while the emiT group it was the same as in the NIST experiment, i.e. several hundred times lower. However, the values of the ionic background differ by only 5-6 times of magnitude. The light ions, together with the beta protons, should have a delay time comparable to 1  $\mu$ s. 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 4 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  $\mu$ s.

Fig 4 presents the impulse forms on the electron-proton detector. As was pointed out above, the significantly delayed impulses of low amplitude correspond to ion impulses, and the impulses from protons are simply invisible due to a presence of a wide electron impulse of high amplitude. Namely this fact explains the dead zone around zero on the spectrum of electron-ion coincidences on Fig. 3.



**Fig. 4.** 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

**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 on Fig 6. 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 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.

**Fig. 5** 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.

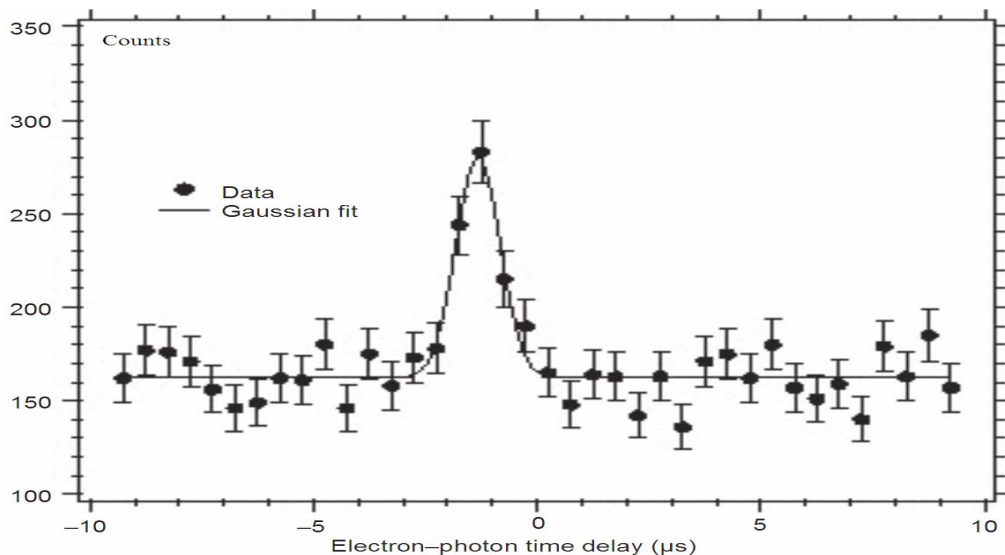
Comparing Fig. 1 and 5, it becomes clear that if we ignore the first leftmost peak with the maximum in channel 103 in Fig. 5, the spectrum of double e-p coincidences will resemble the spectrum of triple e-p- $\gamma$  coincidences on Fig. 1. The peak with the maximum in channel 106 on Fig. 5 is connected to the left peak of false coincidences on Fig. 1, and the peak with the maximum in channel 120 on Fig. 5 is connected to the right peak of e-p coincidences on Fig. 1. 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. Using the method of response function, one can confidently define our double-humped background: the narrow peak with the maximum in channel 106 on Fig. 5 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 on Fig. 1, and the second peak in this double-humped background on Fig. 5 is the response to the peak in channels 117-127 on Fig. 1 (or this peak is response to proton registration).

When discussing the similarities between the spectra on Fig. 1 and Fig. 5, it is important to note that the response peak on Fig. 5 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 on 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 on Fig 5 versus the first peak on Fig 1 with the maximum in channel 100. The value of this delay is equal to the length of the gamma quantum impulse signal front 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 on Fig 5.

As for the wide, almost indistinguishable peak in channel 165 on Fig. 5, its influence on 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  $\mu$ s 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. 6). 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 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 not isotropic emission of radiative gamma-quanta Fig. 3. With the number of observed double e-p coincidences  $N_D = 3.75 \cdot 10^5$  and triple e-p- $\gamma$  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  $\omega=35$  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 our future experiment we will be able to make more definite conclusions about deviation from the standard electroweak theory with experimental error less than 10%.



**Fig. 6** 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].



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  $\mu$ s. 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  $\mu$ s, besides that the diode pulse arrives with significant noise, which makes the thickness of the front pulse line equal to more than 0.5  $\mu$ s (see the photon line on 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  $\theta$  between particle velocity and magnetic field direction. In beta decay, electrons can fly out under any angle  $\theta$ , 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. 3) 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 on Fig 6 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 5). 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 5 completely corresponds to the wide peak on Fig 6. However, as noted above, density of gas molecules remains high even with the pressure of  $10^{-8}$  -  $10^{-9}$  mbar and this atmosphere 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  $B.R. = (3.2 \pm 1.6) 10^{-3}$  ( 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 percents according to estimates.

For last two years we were preparing this new experiment and conducted number of tests for our new electronics. We constructed multi channel 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  $\mu$ s. 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  $\mu$ s 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

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