Characteristic features of double and triple coincidence spectra coupling in the radiative neutron decay

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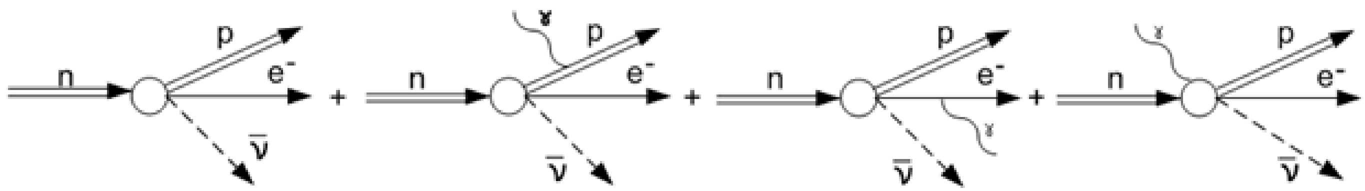
The paper uses the example of radiative neutron decay, which we discovered in 2005 at the TUM (Technical University of Munich) reactor [1], to examine the coupling of double and triple coincidence spectra. To this end, special attention is paid to the electronic system for collecting and processing information received from the electron, proton, and gamma-ray detectors. As demonstrated, in the presence of a significant background gamma-ray, the spectrum of triple coincidences will have, apart from the peak of triple coincidences of the beta electron, proton, and gamma-ray quantum, additional peaks which represent Responses to the peaks in the spectra of double coincidences of beta electron with proton and beta electron with gamma quantum. After processing the spectra using the response Function method, we measured the main characteristic of the radiative beta decay of the neutron, namely its branching ratio. Thus, In this experiment we were the first to measure The branching ratio (B.R.) of radiative neutron decay B.R. = (3.2±1.6)10-3 (where C.L. = 99.7% and gamma quanta energy threshold is equal to 35 Kev) [1]. On the other hand, Theoretical calculations [2] of B.R. according to the Standard Model give 1.5 times lower than this experimental average value, so we recorded additional gamma quanta which are structural gamma quanta emitted by the quarks that a neutron consists of.

[1] R.U. Khafizov et al. JETP Letters, v. 83(1), 2006, p. 5
[2] Yu.V. Gaponov Yu.V., R.U. Khafizov. Phys. Lett. B 379 (1996), p. 7

What is the radiative branch of decay?

- **Among the many rare 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 α 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** $n \rightarrow p + e + \overline{\nu} + \gamma$ **had not been discovered, and all the experiments have been aimed at the study of the ordinary neutron decay branch** $n \rightarrow p + e + \overline{\nu}$
- **However, the study of radiative branches of elementary particle decay occupies a central place in the fundamental problem of searching for deviations from the standard electroweak model.**

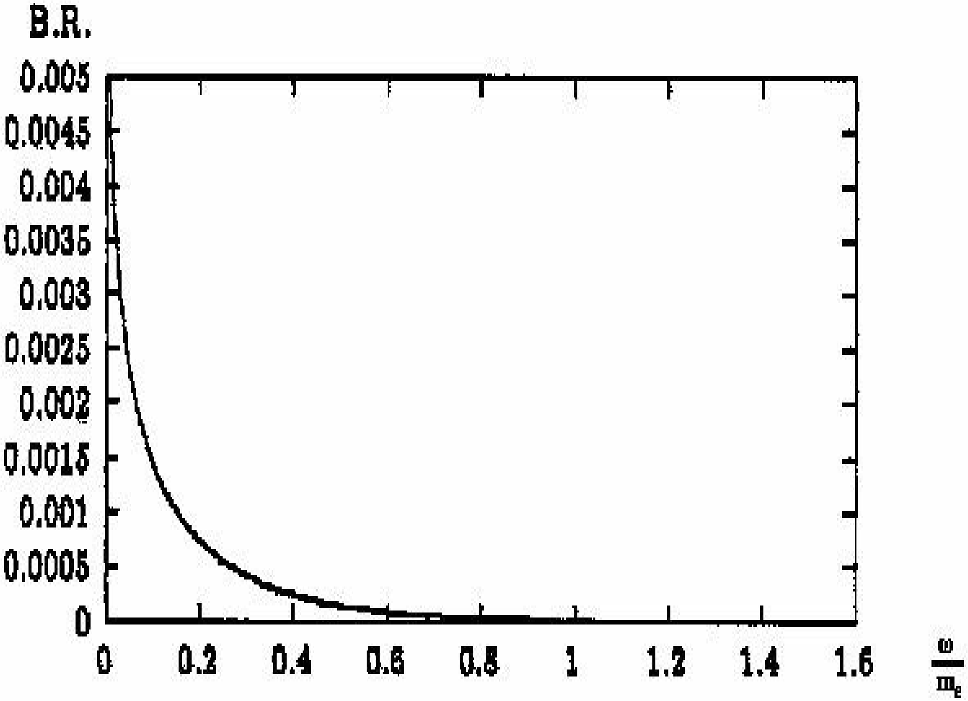


Diagrams of usual and neutron radiative beta decay, last one presents radiation of structure gamma quanta

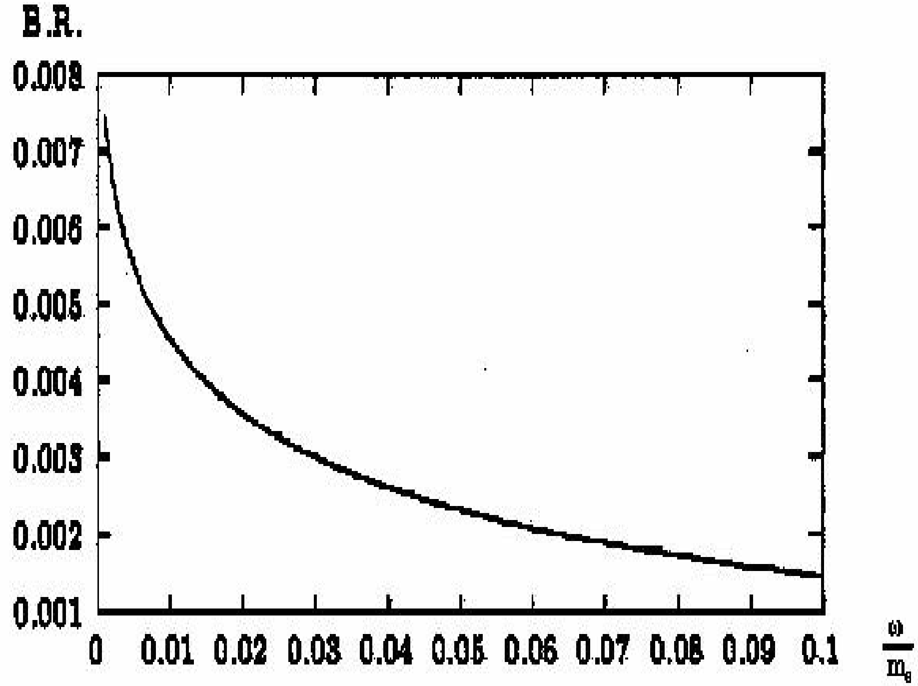
- **of the ordinary decay mode are currently measured with precision of tenths of a percentage point. Under these circumstances experimental data obtained by different groups of experimentalists can be reconciled only by taking into account the radiative corrections calculated within the framework of the standard theory of electroweak interactions. This means that experimental research of the ordinary mode of neutron decay has exhausted its 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 decay branch to the next step, namely, to the experimental research of the radiative decay branch.**
- **The main value for radiative neutron decay is branching ratio**

  BR = I(radiative decay) / I(ordinary decay) = (N(e,p,γ) / N(e,p))k_{gejm}= (N_T / N_D)k_{geom} ,
- **where the number of triple N_T and double N_D coincidences have to be taken directly from the experimental spectra of triple and double coincidences, thus the measurement of BR is really the measurement of the double e-p coincidences spectrum and the triple e-p-γ coincidences spectrum. Without analyzing these experimental spectra it is impossible to say anything about the experimental measurement of the BR value.**
- **The measurement of BR is a relative experiment, it is not an absolute experiment, therefore, there should be fewer uncertainties around intensity measurement in this case.**

Theoretical value of BR calculated in the frameworks of Standard Model (Phys. Lett. 1996, B 379, p.7)



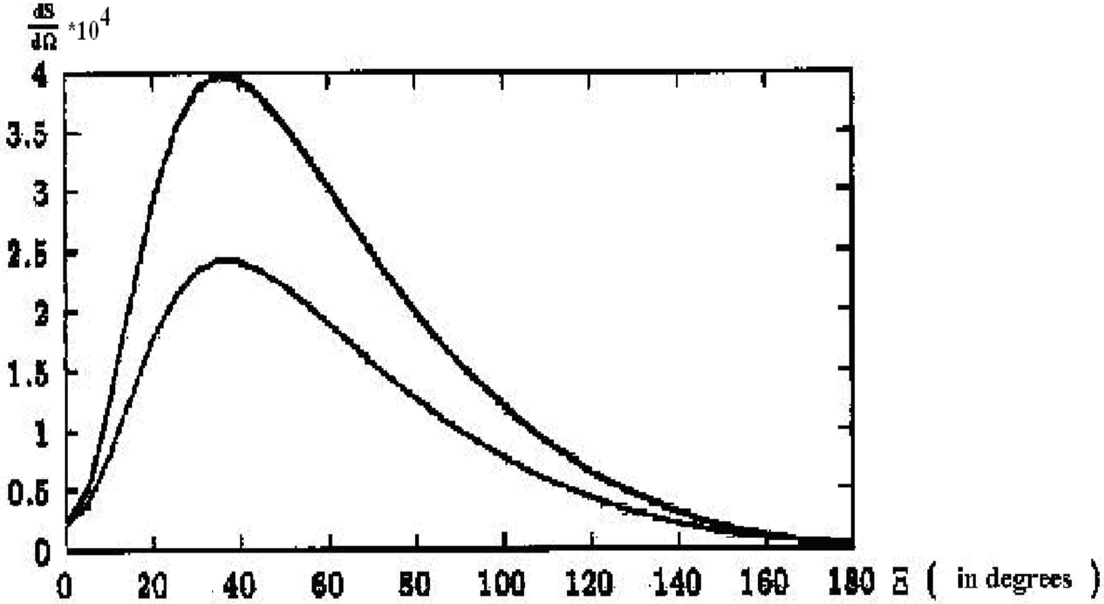
The expected Standard Model branching ratio for radiative neutron beta decay (summed over all gamma energies larger than the threshold gamma energy ω) as a function of ω/m_e.



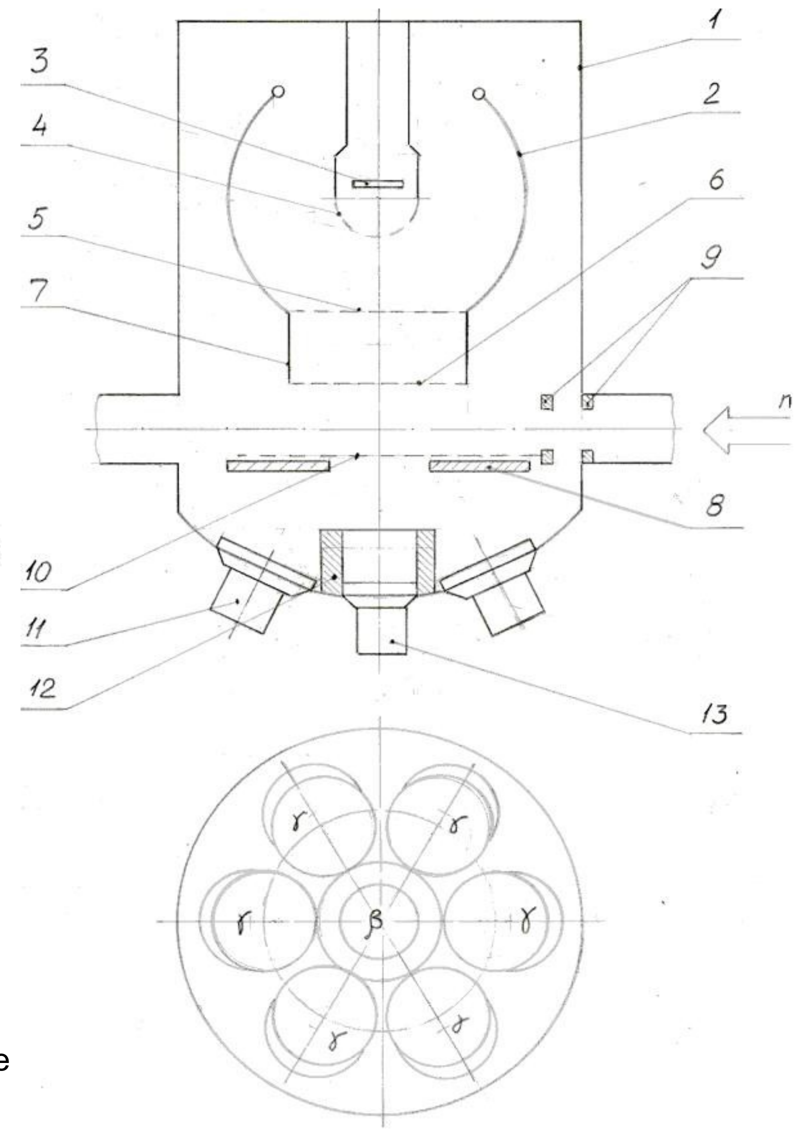
The same but with detail scale for ω/m_e

$BR=2\cdot10^{-3}$ for radiative gamma quanta energy more than 35 keV

Angular distribution of radiative gamma quanta and schematic lay-out of the experimental setup (JETPh Letters, Jan., 2006, vol.83(1), p.5)



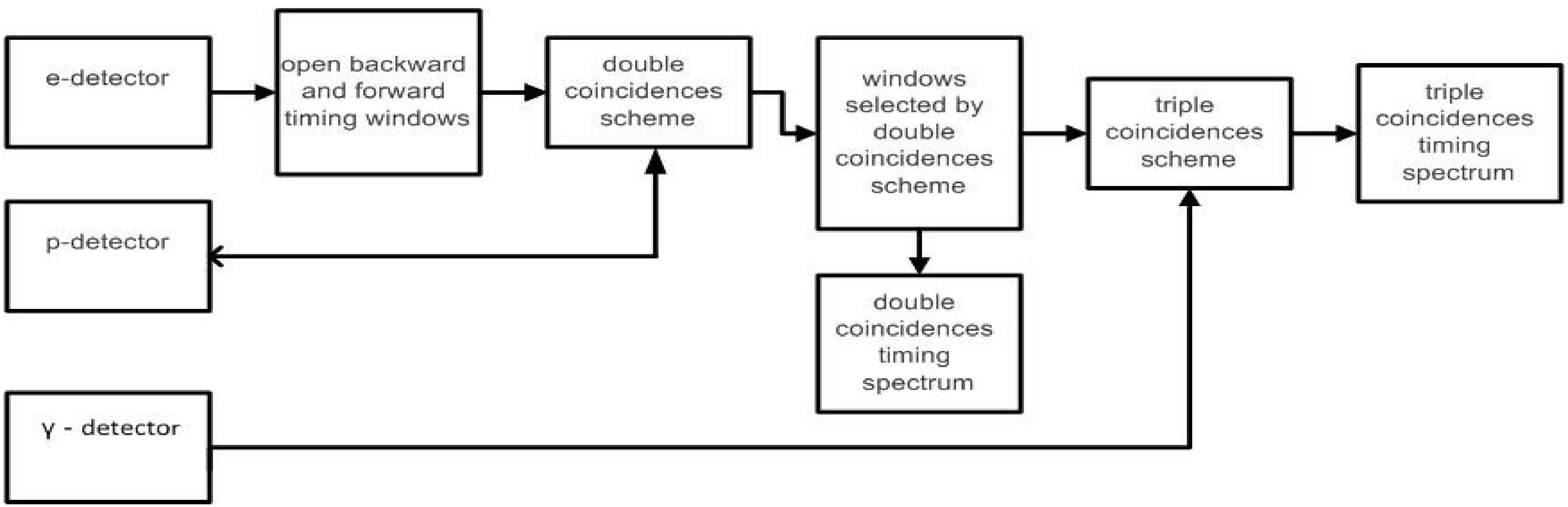
Dependence of the radiative decay spectrum S on the angle Ξ between the photon and the electron momenta (upper curve for a threshold gamma energy of 25 keV, lower curve for a threshold gamma energy of 50 keV)



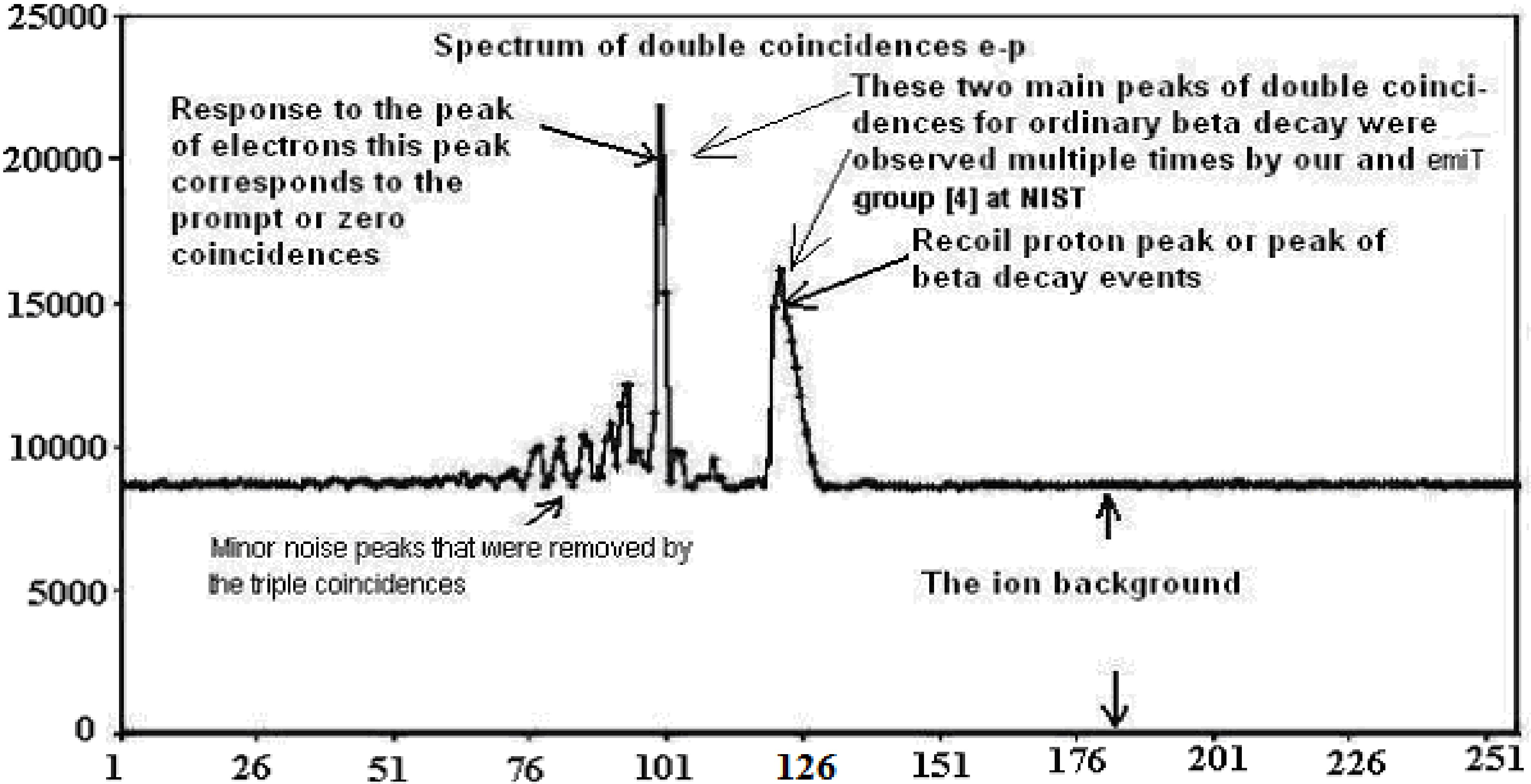
Schematic lay-out:
vacuum chamber, (2) spherical electrodes to focus the recoil protons (at 18-20 kV) on the on the proton detector (3), (4) grid for proton detector (at ground potential), (5) & (6) grids for time of flight electrode, (7) time of flight electrode (at 18-20 kV), (8) plastic collimator (5 mm thickness, diameter 70 mm) for beta-electrons, (9) LiF diaphragms, (10) grid to turn the recoil proton backward (at 22-26 kV), (11) six photomultiplier tubes for the CsI(TI) gamma detectors, (12) lead cup, (13) photomultiplier tube covered by plastic scintillator of electron detector.

The electronic block scheme of processing and collecting information for our experiment.

- Forward (100 channels of 25 ns) and backward (100 channels of 25 ns) windows are opened by the signal from the electronic detector, then the double coincidences circuit receives signals from the p-detector, which are recorded in the corresponding channel of the open windows. The double coincidence scheme generates a spectrum of the double coincidences events and selects only double coincidences windows from all the windows opened by the electronic pulse. The triple coincidence scheme then records the signal from the gamma detector to the appropriate channel and forms a triple coincidences spectrum.



Experimental double coincidences spectrum (JETPh Letters, Jan., 2006, vol.83(1), p.5)

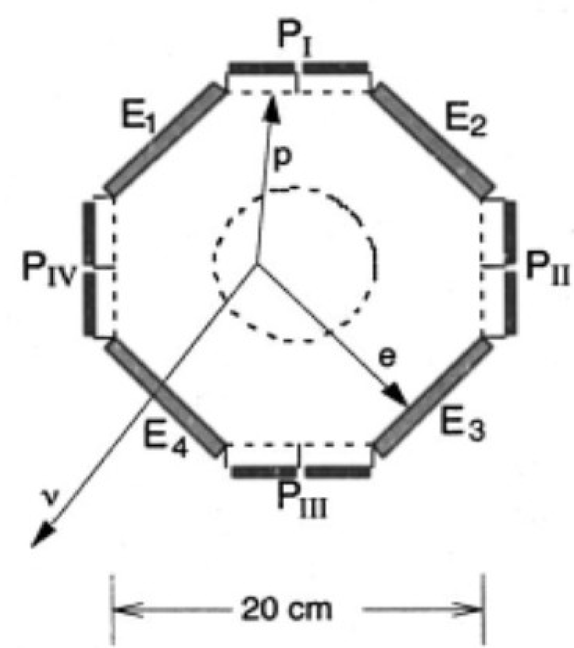


Timing spectrum for e-p coincidences. Each channel corresponds to 25 ns. The peak at channel 99-100 corresponds to the prompt (or zero) coincidences. The coincidences between the decay electrons and delayed recoil protons (e- p coincidences) are contained in the large peak centered at channel 120 (delay time is about 500 ns). This peak gives the number of double coincidences events $N_D=3.75\cdot10^5$ for BR measurement. Minor noise peaks before the peak of zero coincidences were not stable during statistics collection, disappearing at nighttime and on weekends, when the noise in the electric circuits was minimal.

Experimental double coincidences spectrum measured by emiT group at NIST (Phys. Rev. C, 2000, vol.62, p. 055501)

[redacted]

e-p coincidence spectrum with
two main peaks and ion background

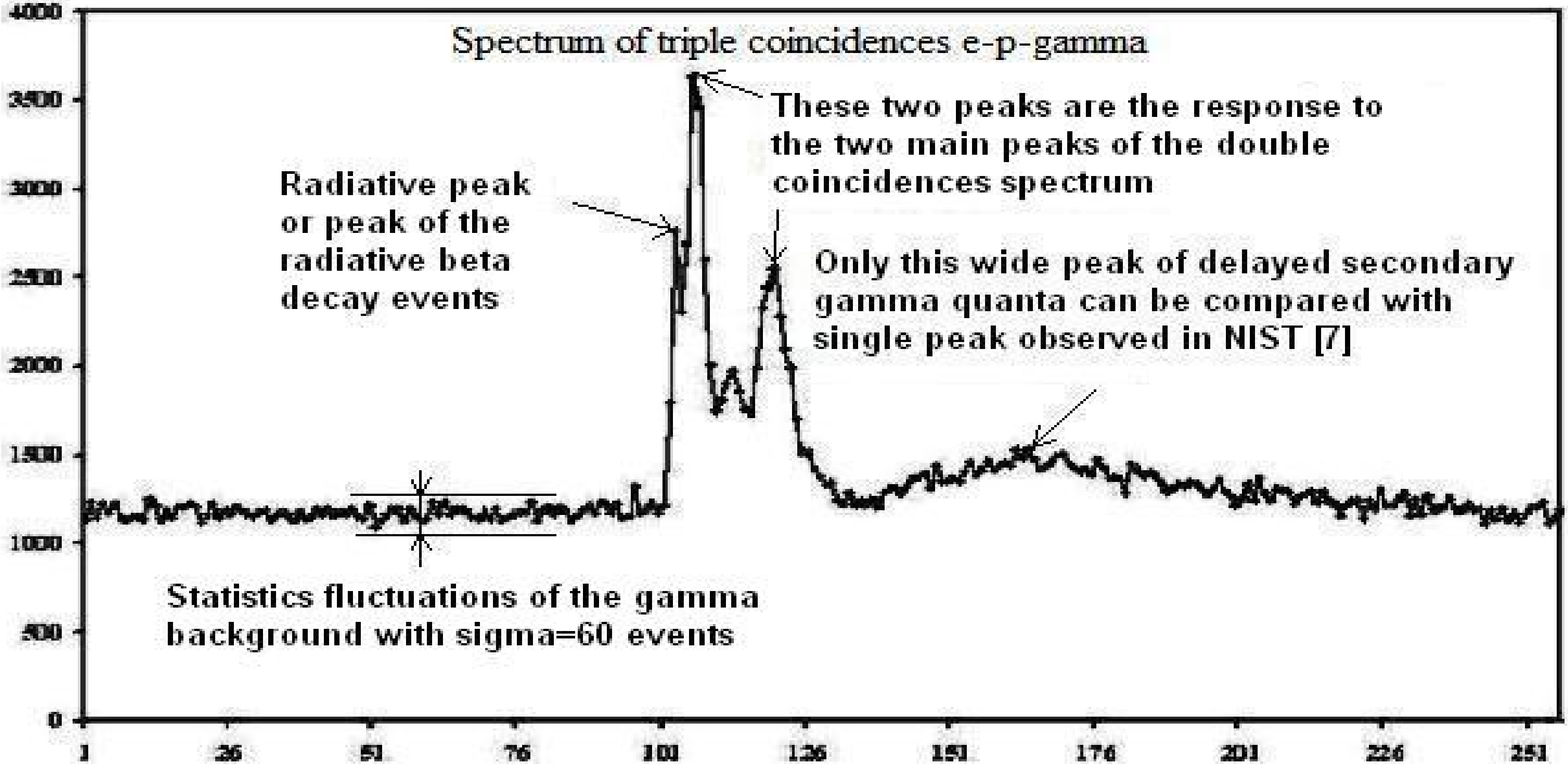


Schematic lay-out of
experimental setup

Comparison of our and emiT group double coincidences spectra
Main conclusions:

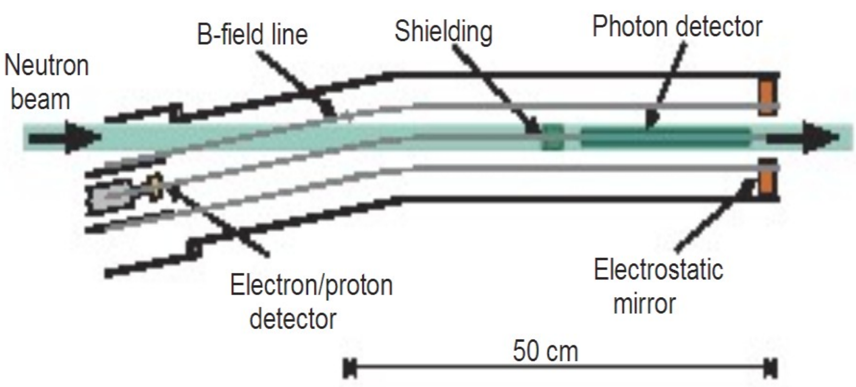
- All experiments observed two, namely two, peaks on the spectra of double coincidences, but only the emiT group and our group published both peaks without any distortions
- The presence of the first peak (of false or zero) coincidences points to the presence of a response in the double-channel electron detecting system in the proton and electron channels. This peak, located at the time of the electron registration, is the response peak to electron registration. It has no any physics nature.
- From the previous two points it follows that the background, against which the main peak is observed and which is used to register the events of neutron beta-decay, is not homogenous but rather contains a response of the registering equipment. From this it follows that to analyze the time spectra accurately, it is necessary to use the response function method.
- Using this method allows to distinguish the heterogeneous background with all the response peaks of the registering equipment from the experimental data.
- Delay times between the first peak, i.e. the equipment response to electron registration, and the second physical peak, i.e. the peak representing the total number of registered delayed electron-proton coincidences, correspond to the estimates that take into account the geometry of experimental equipment and the electric fields used in our experiments – both in our results and the results of the emiT group.
- The main parameters of the response function are determined by solving an integral equation using the input and output experimental spectra.
- The location of the first response peak in the two spectra of double coincidences is determined by the time of electron registration. In both experiments the impulse that arrived through the electron channel opened two identical time windows, “before” and “after”. Thus, it is position in the center of the overall time window.
- The value of the response peak to electron registration is determined by the parameters of the electron-proton detection system (the form and total length of the pulses, the length of fronts, the background value, etc.)
- The width of the response peak is determined primarily by the noise in electric chains feeding the electron equipment.
- From the analysis of the double coincidences it follows categorically that the spectrum of triple coincidences (between the electron, proton and gamma quantum) also has a heterogeneous background and should show not one but two response peaks. The first would be the response to electron registration and the second would be the response of the detecting system to the registration of delayed protons (recoil protons from the beta decay).
- Aside from the two main speaks, both spectra clearly show a homogenous horizontal background created by ions registered by the proton detector. The value of this background is significant in both cases.
- The most important value in these spectra is the ratio of the second beta-decay peak value (used in our experiment to find the value of the total number of registered neutron decays, defining B.R. denominator) to the value of the homogenous ionic background. In both spectra this ratio is close to 1. This very gradual reduction of the background versus the effect, depending on the pressure in the vacuum chamber, is explained by Avogadro law, which can give that this ratio depends on the pressure as a cubic root . The ratio of pressures in our experiment and the emiT experiment is about 100, but the background changed versus the effect only by several times of magnitude.
- From the points above it follows that the most important aim for the next experiment is improvement of the electron detector system and its supporting software.

Experimental triple coincidence spectrum e-p-γ (JETPh Letters, Jan., 2006, vol.83(1), p.5)

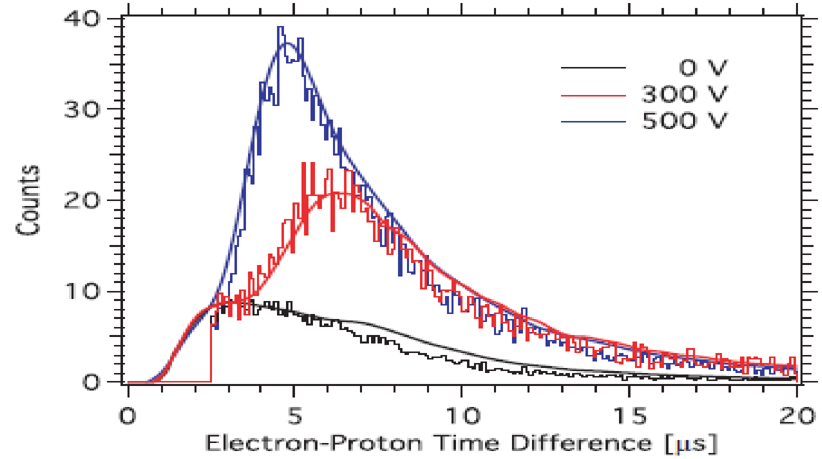


Timing spectrum for triple e-p-γ coincidences. In this spectrum, three main peaks in channels 103, 106 and 120 can be distinguished.The leftmost peak in 103 channel among these three main peaks is connected with the peak of radiative decay events. This peak gives the number of triple coincidences events N_T for BR measurement. This peak was always stable, it never "migrated" to a different channel and it grew at a stable rate, regularly collecting the same number of events during the same stretch of time. The final value of radiative events, namely the value of triple coincidences N_T, in our experiment with an error of 3σ was equal to N_T =360±180 events. After we obtained the number of beta-decay events forming the beta decay peak on the spectrum of double coincidences N_D=3.75·10^5 and calculated the geometric factor of our experimental equipment k=3.3, we obtained the BR= k · N_T /N_D value of B.R. = (3.2+-1.6) 10^{-3} (with C.L.=99.7% and gamma quanta energy over 35 keV).

Experimental setup and double coincidences electron-proton spectrum measured by R.L. Cooper, T. E. Chupp and M.S. Dewey et al at NIST (Phys. Rev. v. C81, p.035503 (2010))



Detection scheme for measuring the radiative decay of the neutron. The cold neutron beam traversed the bore of superconducting solenoid (4T). The decay zone is surrounded by photon detectors. The combined electron-proton detector was held at a high negative potential 22.5 kV to accelerate the low-energy recoil protons.

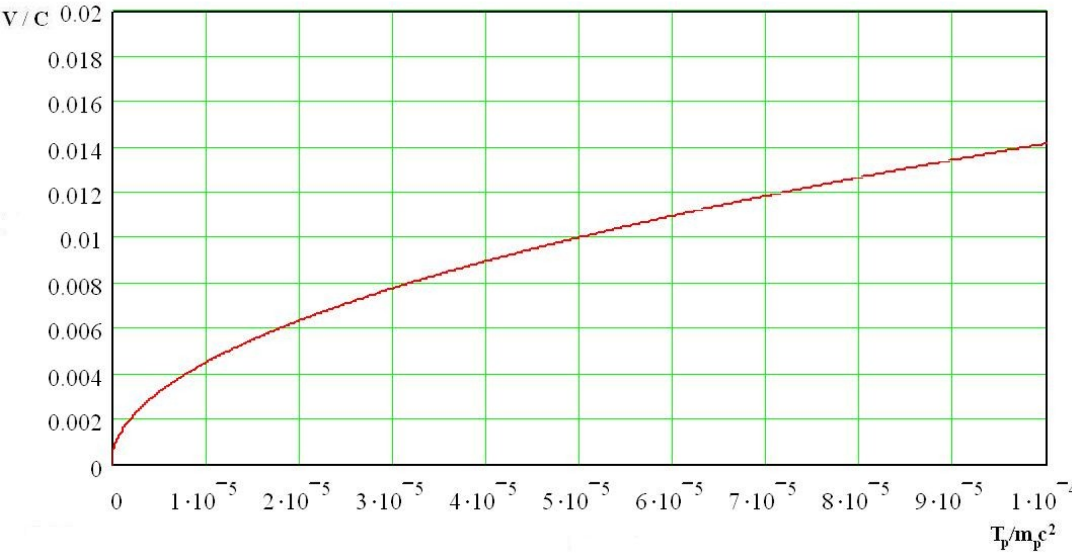


The proton peak, obtained in the NIST experiment. The location of the peak's maximum and its significant width differ from our and the emit results by one and two orders of magnitude. The location and the width of the peak also deviate by one and two orders of magnitude from the elementary estimates of delay times (see below).

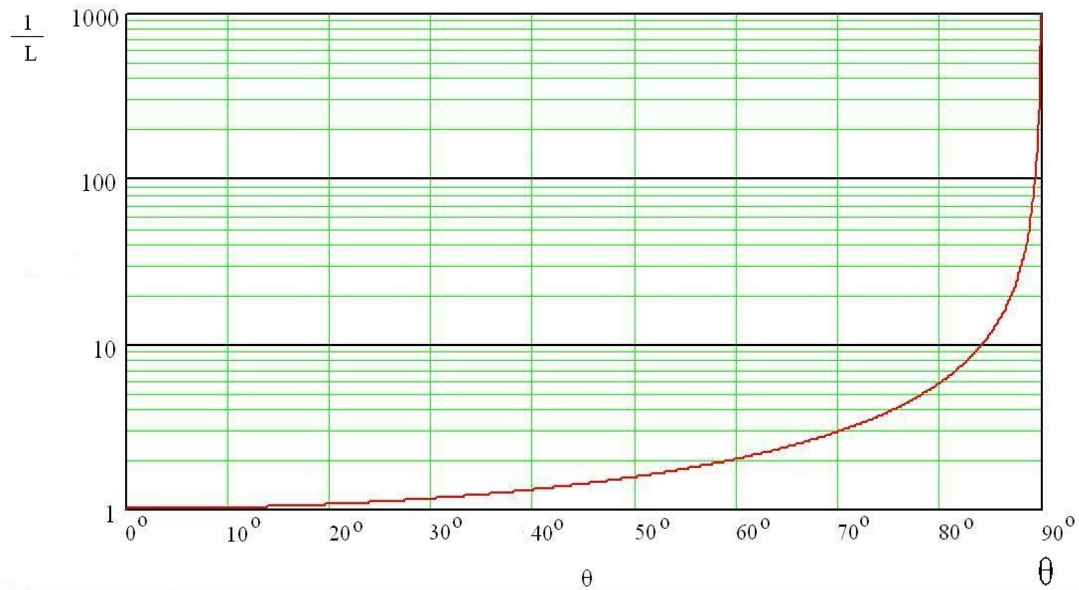
The significant deviation obtained is explained by the fact that the peak in the NIST experiment consists not of beta-decay protons, but rather of ions. The density of gas molecules inside the equipment is proportional to pressure and according to the Avogadro's Law is at the order of 10^7 mol/cm^3 even at the pressure of 10^{-8} – 10^{-9} mbar. This is a very significant number, which allows to distinguish the ionic background in the presence of ionizing radiation. The energy of beta-electrons significantly exceeds the energy of ionization. Besides, the probability of beta-electrons creating ions 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 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 below Figure 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.

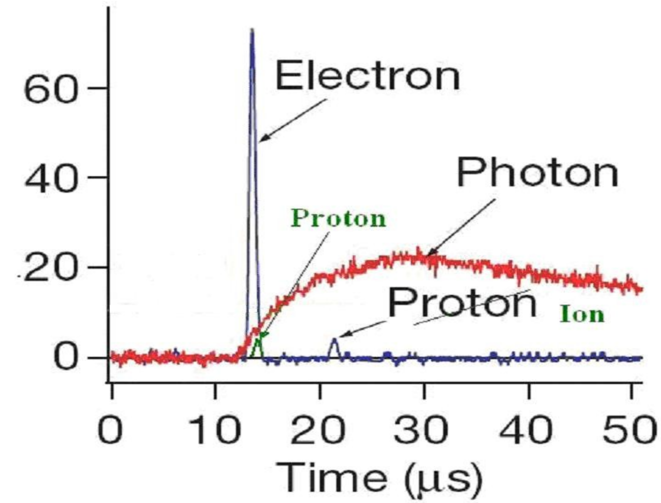
Figures for estimating the time of delay for recoil proton

Dependence of v/c for proton on ratio of its kinetic energy T_p to $m_p c^2$



Dependence of the ratio of the spiral length *l* to the distance L between the point of decay and the detector on the angle θ between the velocity of this particle and the direction of the magnetic field.

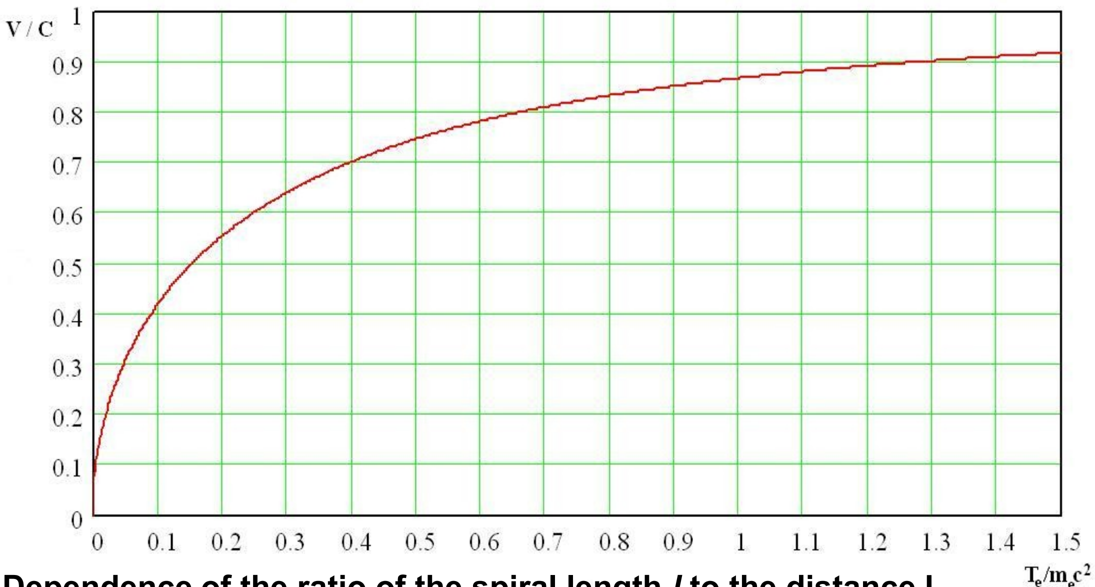


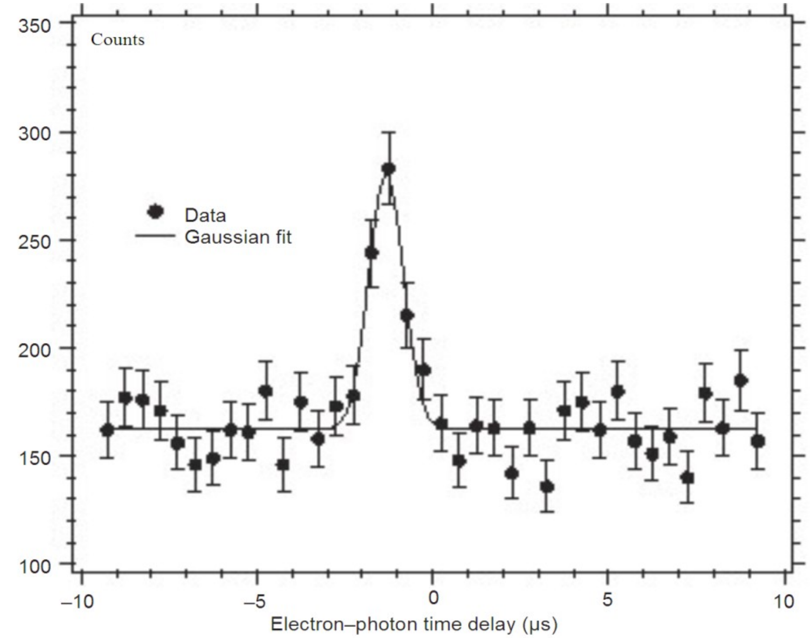


In beta decay, the protons have the small initial energy (less than 750eV), therefore the angle θ is determined by the angle between the electric and magnetic field lines which is definitely less than 30°. The magnetic field cannot change the speed of charged particles it can twist a line trajectory into a spiral only. The length l of this spiral depends on angle θ between particle velocity and magnetic field direction. As it follows from graph *l*/L, the maximum delay would be increased not more than on 30%. So, strong magnetic field can not increase the time of delay by several orders of magnitude. The time of delay about several µs should be for the background ions only (which also have maximal initial energy 750eV) and for the protons the time of delay should be the same as in double coincidences spectra of our and emiT group. In this case the small proton signal should be under the electron one and can not be registered by the combined electron-proton detector. The strong magnetic field can not be used for the identification of the ordinary beta decay events because it mixes the small number of decay protons with the large number of background ions and the beta decay peak is disappeared on the e-p spectrum.

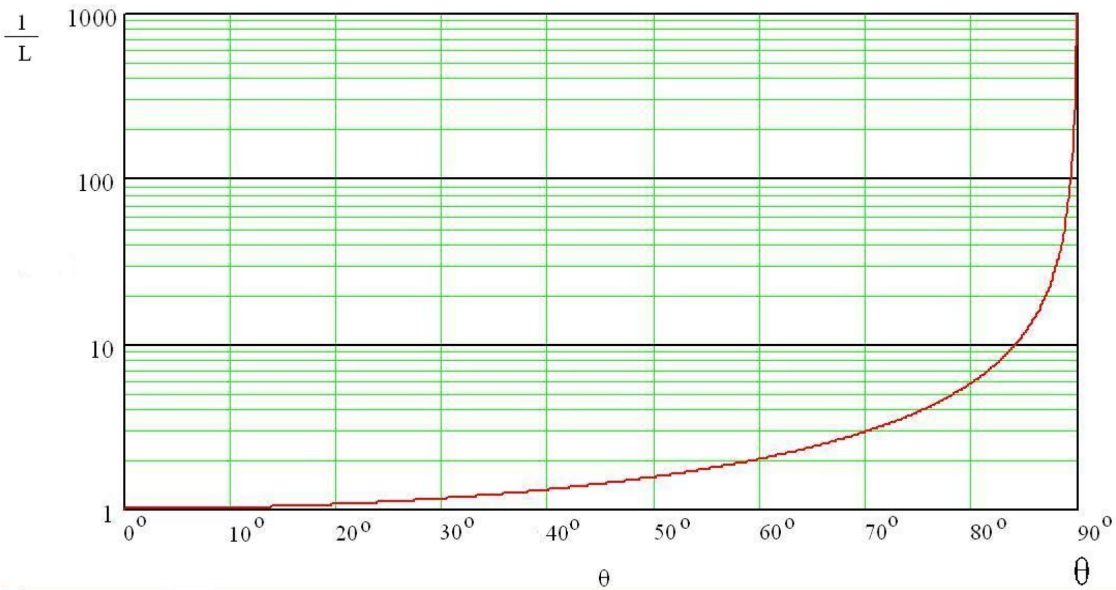
Figures for estimating the time of delay for beta electron

Dependence of v/c for electron on ratio of its kinetic energy T_e to m_ec^2





Dependence of the ratio of the spiral length *l* to the distance L between the point of decay and the detector on the angle θ between the velocity of this particle and the direction of the magnetic field.



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 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 by two orders than microsecond.

Next experiment on the radiative neutron decay and 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±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 Phys. Rev. C, 2000, vol.62, p. 055501**
- **Unfortunately we cannot say same for another experiment measuring the radiative neutron decay published in Nature v. 444, p.1059 (2006). 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.**