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The upper limit of the branching ratio for radiative beta-decay of free neutron

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We conducted the experiment on radiative neutron beta-decay on a intensive cold neutron beam at ILL during April and May of 2002. This work is dedicated to the analysis of the methodology and the results of the study. The main outcome of this experiment is the branching ratio (BR) for the rare neutron decay mode in the gamma-quanta energy region from 35 to 100 KeV. The limit obtained is BR $< 6.9\cdot 10^{-3}$ (90% C.L.), which is only a few permilles greater than the theoretical BR value, calculated within the standard weak interactions model.

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1. Introduction. This experiment is the first step in the research of the radiative neutron beta-decay where, along with the usual three particles (i.e. electron, antineutrono and proton), another particle is created, namely, the gamma-quantum:

$$n \to p + e + \bar{\nu} + \gamma.$$

It is necessary to note that this decay branch is the most intensive of all the rare elementary particle decay modes, and is therefore well investigated for practically all elementary particle decays where charged particles are formed in the final state. However, this branch is yet to be discovered for the neutron [1]. Calculations of the gamma-quanta spectrum were conducted in the framework of standard electroweek theory and the branching ratio (BR) for this decay mode as a function of the gamma energy threshold was given in refs. [2, 3].

The experiment was conducted in the radiative gamma-quanta energy region from 35 to 100 KeV, and for this region the theoretical BR value is about one permille [2, 3]. It is not such a difficult task to measure this relatively large value, as a rather significant background could be overcome with the help of triple electron, gamma-quanta and recoil proton coincidences. The presence of such a coincidence will be the factor used to identify a radiative neutron decay event. An ordinary neutron beta-decay is then defined by the double coincidences of electron and recoil proton. This double coincidence scheme has already been used in measuring the emission asymmetry [4, 5] of the decay electron by the joint group of physicists from PNPI (Gatchina) and RSC "Kurchatov Institute" (Moscow). The setup, used in those experiments, is upgraded now for the conduction of the experiment on radiative neutron decay suggested here.

This upgrading was realized by placing an additional gamma-quanta detector in the existing vacuum chamber, the size and the geometry of it allowing to do so. However, the simple addition of a third gamma-quanta detector to the two detectors for the decay electrons and recoil protons would not suffice by itself. The point is that in this experiment, besides the non-correlated background there is also a correlated background of bremstrahlung gamma-quanta which fully simulates the desired fundamental process. It is therefore necessary to concider this problem in more detail.

Indeed, when measuring the BR a correlated background will occur, which is impossible to decrease even with triple coincidences of the electron, the photon and the proton. This background is connected with bremsstrahlung emission of the electron traveling through the plastic scintillator, which completely simulates the events of radiative neutron decay and is quite significant even when the thickness of the plastic scintillator is only 3 mm. The idea of diminishing this correlated background centers around using the spatial resolution. If a sectioned *e*-gamma detector is used and electron and gamma-quanta are registered in different sections then the background could be overcome completely, because the bremsstrahlung emission occurs only in the section that registers electrons. Within the electroweak interaction model, calculations demonstrate one important particularity of radiative emission for the rare neutron mode being studied: it is not forward directed, as the bremsstrahlung, but achieves the maximum intensity of radiative gamma-quanta emission at the angle of 35 degrees with respect to the electron takeoff direction. It was this particularity of radiative neutron decay that we had realized in the methodology of this experiment, having placed the gamma-detectors at 35 degrees to the electron detector. In this case, part of the statistics is lost, of course, but as can be seen from ref. [3] and Fig.4 in it this is only a small fraction.

2. Experimental Setup. The experimental set-up is shown schematically in Fig.1. The intense cold neutron beam passes through a rather long neutron guide in which is installed a collimation system made of LiF diaphragms, placed at regular distances of 1 m. The neutrons enter the vacuum chamber (*1*) through the last diaphragm (*10*) that is located directly before the decay zone. This zone is observed by three types of detector: the micro channel plate (MCP) proton detector (*3*), the electron detector (*14*) consisting of a 7 cm diameter and 3 mm thick plastic scintillator, and six gamma detectors (*12*) that are located on a ring centered around the electron detector and which consist of photomultiplier tubes each covered with a layer of CsI(Tl) scintillator. The thickness of these 7 cm diameter CsI(Tl) scintillators is 4 mm and has been selected so as to have a 100% detection efficiency for photons with energies up to 100 keV. The six gamma detectors surround the electron detector (see ref. [3]) at an angle of 35° and are shielded from it by 6 mm of lead (*13*).

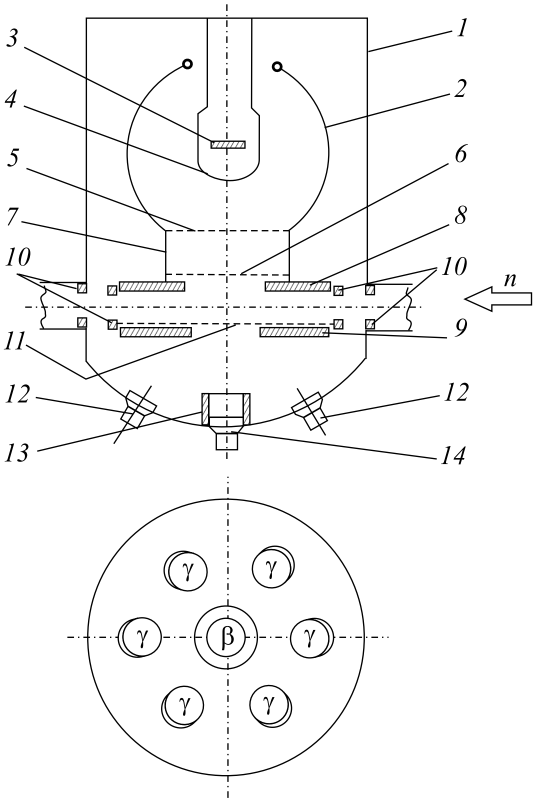

Fig.1. Schematic lay-out of the experimental set-up: *1* – vacuum chamber, *2* – spherical electrodes to focus the recoil protons on the detector (at 13–20 kV), *3* – proton detector, *4* – grid for proton detector (at ground potential), *5* & *6* – grids for time of flight electrode, *7* – time of flight electrode (at 13–20 kV), *8* – plastic collimator (5 mm thick, diameter 70 mm) for recoil protons, *9* – plastic collimator (5 mm thick, diameter 70 mm) for beta-electrons, *10* – LiF diafragms, *11* – grid to turn the recoil proton backward (at 22–26 kV), *12* – six photomultiplier tubes for the CsI(Tl) gamma detectors, *13* – lead cup, *14* – photomultiplier tube for the plastic scintillator electron detector

By requiring a coincidence between the electron detector and any of the gamma detectors the bremsstrahlung background can in principle be overcome completely, because bremsstrahlung emission occurs only in the section that registers the electron. In this case, part of the statistics is lost, of course, as can be seen from Ref.[3] and Fig.4 in it. However, the neutron beam intensity of 10^{12} n/s in our experimental chamber is sufficiently high to still allow for a good count rate. Recoil protons, formed in the decay zone, pass through a cylindrical time of flight electrode (*7*) in the direction of the proton detector (*3*) and are focused onto this detector with the help of spherical focusing electrodes (*2*). The focusing electrostatic field between the high voltage spherical and cylindrical electrodes (*2*) and (*7*) is created by the grids (*5*) and (*6*) at one side and by the proton detector grid (*4*), at ground potential, at the other side. It is important to note that the recoil protons take off isotropically from the decay point. In order not to loose half of the protons emitted, an additional grid (*11*) is added on the other side of the decay volume. The potential difference between the grid (*11*) and the grids and electrodes at the other side of the decay volume in principle assures a 4π solid angle coverage for the recoil protons. At present this 4π solid angle coverage is not realized due to the presence of the plastic collimator (*8*) with a hole of 70 mm diameter, i.e. the diameter of the decay zone, on the side of the proton detector. For future measurements this collimator will therefore be removed, which will increase the proton count rate by about a factor 50.

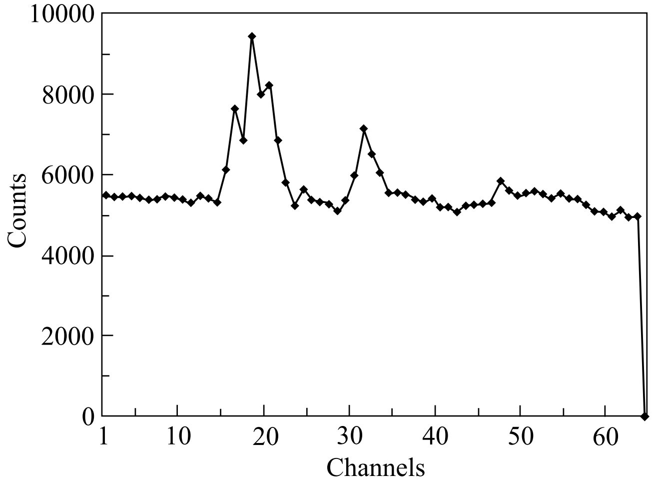

Fig.2. Timing spectrum for $e-p$ coincidences. Each channel corresponds to 25 ns. The peak at channel 17 corresponds to the prompt (momentary) coincidences. The coincidences between the decay electrons and delayed recoil protons ($e-p$ coincidences) are contained in the large peak centered at channel 30

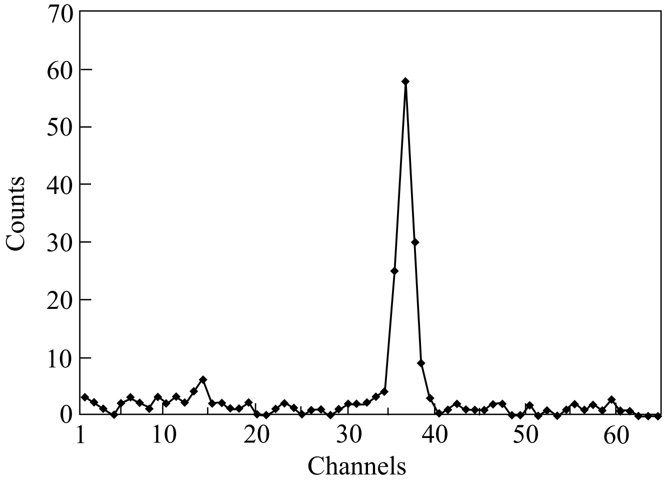

Fig.3. Timing spectrum for triple $e-p-g$ coincidences (peak centered at channel 35). Each channel corresponds to 25 ns

The start signal that opens the time windows for all detectors is the signal from the electron, registered in the electron detector. For an event to be considered as a radiative neutron decay event simultaneous signals from the electron detector and one of the gamma detectors, followed by a delayed signal from the proton detector are required. Besides these triple coincidences also electron-proton coincidences, signaling a neutron decay event, are monitored.

It is important to note here that thanks to the LiF ceramics diaphragm system which was installed in the neutron beam line, the gamma background from the intense cold neutron beam was significantly suppressed. The background level in the gamma detector amounted to about 100 Hz only (at a neutron beam intensity of 10^{12} n/s). If the number of the diaphragms in the neutron guide were doubled, the background of the gamma detectors could be further reduced by another order of magnitude, thus becoming comparable to the noise of the photomultiplier tubes. The count rate in the electron detector was just about 100 Hz. It is very likely that most of this count rate is due to electrons from neutron decay since the count rate in this detector almost immediately dropped to zero when the neutron beam was switched off. The main problem in this experiment was the proton detector background, which turned out to be very sensitive to the vacuum conditions in the experimental chamber. This is discussed in detail in the next section.

3. Results. The experiment itself could be divided into two stages. At the beginning of statistics collection we immediately discovered a peak of triple coincidences, however, the ratio of the triple electron-proton-gamma ($e-p-g$) coincidences to the number of double electron-proton ($e-p$) coincidences was about $5\cdot10^{-2}$, which exceeds the theoretical value more than one order. At the same time, at the beginning of the experiment we had a rather poor vacuum and we consitantly registered a very high ion background in our proton detector. These results at the beginning of our experiment are best demonstrated in the time spectra given on Fig.2,3.

Spectra of double $e-p$ coincidences are given at the Fig.2, and triple $e-p-g$ coincidences are given at the Fig.3. Two peaks can be clearly seen on Fig.2: the so-called peak of false or momentary coincidences, which occurs when the proton detector registers backward scattered bremstrahlung gamma-quanta (see Fig.2), caused when the electron gets into the electron detector, this peak (in the 15 channel area) corresponds to the physical zero of recoil proton delay time countdown. The recoil protons, in turn, form the second peak (from channels 30 to 40) of electron coincidences with delayed in time recoil proton (peak of $e-p$ coincidences). A rather significant ion background could be seen here as well. At the Fig.3, one can clearly see a peak of triple coincidenes of electron, gamma-quanta and delayed recoil proton (from channels 30 to 40, which corresponds to the position of the proton peak at the Fig.2, we artificially shifted this peak under the peak of $e-p$ coincidences, of course, realy this peak coresponds to position of momentary coincidence peak). The numerical analysis of the spectra, shown in Fig.2 and 3, gave a BR limit at the level of $5\cdot10^{-2}$, which exceeds the theoretical value more than one order. The results obtained at the first stage of the experiment, when on one hand we saw this large BR value with a very high ion background and on the other hand we had poor vacuum, forced us to analyse situation in more detail. The analysis showed that our vacuum chamber was filled with vapors of used oil from our old oil pumping system, installed on the vacuum chamber. We decided to replace this system, after which vacuum in the chamber improved, reaching the value of $7 \cdot 10^{-5}$ mbar. After that we started collecting statistics again and found that it's taking much longer than the first time to obtain the peak of triple coincidences and that the ion background in the proton detector fell almost by two orders.

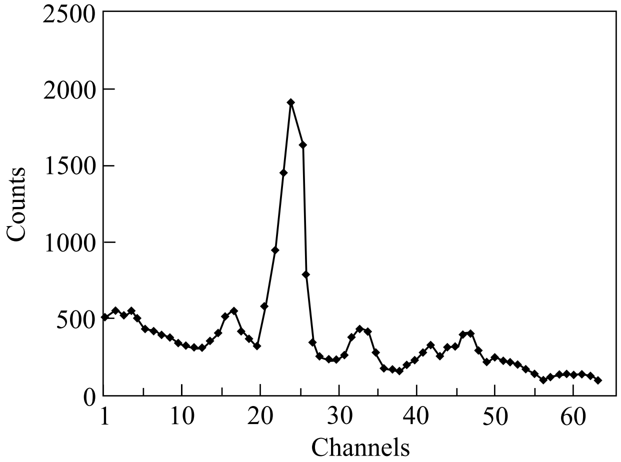

Fig.4. Timing spectrum for $e-p$ coincidences. Each channel corresponds to 25 ns. The peak at channel 17 corresponds to the prompt coincidences. The coincidences between the decay electrons and delayed recoil protons ($e-p$ coincidences) are contained in the large peak centered at channel 24

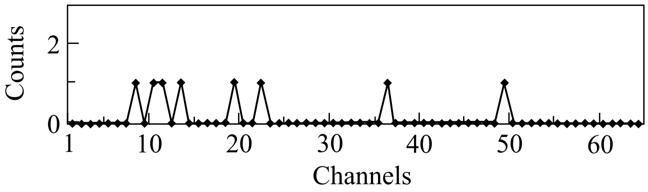

Fig.5. Timing spectrum for triple $e-p-g$ coincidences. Each channel corresponds to 25 ns

The results obtained in the remaining beam time, with a vacuum of about $7 \cdot 10^{-5}$ mbar, are presented in Fig.4 and 5. Fig.4 shows the electron-proton coincidence timing spectrum, while the corresponding triple electron-proton-gamma coincidence timing spectrum is shown in Fig.5. The first peak in Fig.4, centered at channel 16 contains the prompt coincidences between backward scattered bremsstrahlung gamma-quanta that are generated by electrons penetrating into the electron detector and are registered by the proton detector. The central position of this peak corresponds to $t=0$ for the detection of the delayed recoil protons. The second peak (centered at about channel 24) contains the coincidences between electrons and recoil protons ($e-p$ coincidence peak). The distance between momentary coincidence peak and the $e-p$ coincidence peak on Fig.4 is less than the distance between these two peaks on Fig.2 due to an increase of high voltage in the electrodes (a sharp fall of the ion background allowed to increase the high voltage in the electrodes). A comparison of these two figures also shows that when the vacuum improved, the value of the momentary coincidences peak declined sharply. The smaller secondary peaks at the right-hand side of the main peak on Fig.4 are most probably connected with a small number of those recoil protons that, after being reflected from plastics (*8*) and (*9*) on Fig.1, did get into the hole of plastic (*8*) and were registered by the proton detector (*3*). From the data presented in Fig.4 and 5 an upper limit for the branching ratio for radiative neutron decay in the energy region from 35 keV to 100 keV could be deduced. For this, it is important to note that the radiative photons are emitted anisotropically [2]. The triple coincidence count rate N_T can be expressed as

$$N_T = \frac{N_D}{\varepsilon_e \Omega_e \varepsilon_p \Omega_p} \varepsilon_e \Omega_e \varepsilon_p \Omega_p \varepsilon_\gamma \Omega_\gamma f \, \mathrm{BR} \qquad (1)$$

where N_D is the $e-p$ coincidence count rate and ε_i and Ω_i ($i = e, p, \gamma$) are respectively the efficiencies and the solid angles for the electron detector, the proton detector and the six gamma detectors. Further, the product $\Omega_\gamma f$ stands for the integral of the normalized photon-distribution function f (which reaches a maximum at 35° [3]) over the stereometric angle of the six gamma-detectors and BR is the branching ratio of the radiative decay mode for the observed energy region. Adopting the procedure suggested by the Particle Data Group [6] to deduce upper limits for Poisson processes when only a small number of events is observed, Eqn. (1) changes to

$$\mathrm{BR} \le k \frac{N_T}{N_D} (\varepsilon_\gamma \Omega_\gamma f)^{-1} \qquad (2)$$

where the factor k stands for the upper limit for the number of radiative decay events when n_0 events are observed. Note that this result is independent of the efficiency or solid angle of both the electron and the proton detectors. For a calculated expected number of background counts of about 1.5 in the region where the triple coincidence peak is expected, and with $n_0 \equiv N_T = 1$ event observed in this region, the procedure described in Ref.[5] yields $k = 3.11$ at 90% C.L. With the number of observed $e-p$ coincidences $N_D = 5382$, $\varepsilon_\gamma = 1$

and $\Omega_\gamma f \geq 0.084$ one then deduces an upper limit of $6.9 \cdot 10^{-3}$ (90% C.L.) for the branching ratio of radiative neutron decay in the energy region from 35 to 100 keV.

It is interesting to note here that the maximum $e-p$ coincidence rate reached during the experiment amounted to several events per minute. However, estimates show that this rate could be increased by about two orders of magnitude, corresponding to about 10–20 $e-p$ coincidences per second. The main reason for the low count rate during the experiment was the very low efficiency of the MCP proton detector, even after the vacuum problem was solved, caused by the oil vapor which could not be removed from the detector during the beam time.

4. Conclusion. Results from the first experiment aiming to observe the as yet undiscovered radiative decay mode of the free neutron are reported. Although the experiment could not be performed under ideal conditions, the data still allowed one to deduce an upper limit of $6.9 \cdot 10^{-3}$ (90% C.L.) for the branching ratio of radiative neutron decay in the energy region between 35 and 100 keV. This value has the same order of magnitude as the theoretical prediction based on the standard model of weak interactions [2].

Taking into account the fact that the experimental conditions can still be significantly optimized, an $e-p$ coincidence count rate of 10–20 events per second is within reach. Together with the standard model prediction for the branching ratio of this decay mode, this would correspond to a triple $e-p-\gamma$ coincidence rate of several events per 100 seconds. This can easily be observed with the current experimental set-up, which is now being optimized with a view to performing such an experiment. The aim of that experiment will then not only be to establish the existence of radiative neutron beta decay, but also to study the radiative gamma spectrum in more detail.

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