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ASSESSMENT OF THE PARAMETERS OF A SETUP FOR SEARCHES FOR NUCLEON DECAY AND NEUTRON OSCILLATION BY DETECTING MULTIPLE NEUTRON EVENTS IN MASSIVE SAMPLES

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1. Introduction

The predictions of the great unification theories have roused interest in the experiments designed to search for nucleon decay events and neutron oscillation since such experiments offer the unique possibility of verifying these theories. At present a number of experimental setups is intended for detecting nucleon decay and they have allowed one to observe several events possibly due to this phenomenon. The limits of the nucleon half-life were set at $T_{1/2} = (0.5\text{-}20)\times10^{31}$ years (for different decay channels) [1,2]. Experiments aimed to observe neutron-antineutron oscillation are performed and planned mostly on free-neutron beams [3], but the $n - \bar{n}$ transition may also involve an intra-nuclear neutron. For the lifetimes of iron and oxygen nuclei with respect to the decay induced by neutron oscillation in the nucleus the limits of 0.6×10^{31} years [4] and 2.4×10^{31} years [5] have been reached.

In ref. [6] it was proposed to observe nucleon decay by detecting multiple neutron emission in a massive sample. The analysis carried out in [7,15] shows that in the case of the oscillation of a neutron bound in the ^{208}Pb nucleus and in nucleon decay in the ^{208}Pb nucleus there will be observed multiple neutron emission from these nuclei (on the average, from 15 to 30 neutrons in one event). One can assume [15] that the detection of such neutrons in big facilities ($\gtrsim$ 1000 t) will allow one to reach lifetimes of 10^{33} years with respect to nucleon decay and to nuclear decays induced by the oscillation of a neutron bound in the nucleus.

2. Calculation of the detector parameters

We have performed the calculation of the parameters of an experimental setup designed for detecting multiple neutron emission events in massive samples. The calculation was done by the method described in ref. [8]. The detector was supposed to be assembled from separate cells, some versions of the assembly are shown in Fig.1. With this approach, an increase in the detector mass indicates merely an increase in the cell number. For certainty, the neutron counter parameters were fixed, namely it was supposed that the counters were filled with ^{3}He at a pressure of 4 atm, the counter diameter and length were 1.5 cm and 3 m, respectively. Polyethylene

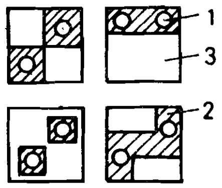

Fig.1. Some detector cells:
(1) neutron counter,
(2) moderator,
(3) heavy substance.

was chosen as a neutron moderator material and lead as a heavy substance. The choice of lead rather than iron is due to the following two reasons: (i) the multiplicity of neutrons emitted from lead nuclei as a result of nucleon decay or neutron-antineutron oscillation is several times higher than that observed in similar processes occurring in iron nuclei, and (ii) neutron absorption in lead is considerably lower than in iron.

We calculated the dependences of the detection efficiency for a single neutron ϵ_n and of the parameter of the dimensions of $\langle R^2 \rangle$ of the detection region for neutrons emitted from one point, upon the characteristics of individual cells of the detector. In this case the main requirement was the obtaining of the maximum value of the quantity $\epsilon_n / \langle R^2 \rangle$, i.e., the provision of a high efficiency of single neutron detection with the minimum possible size of the regions in which neutron detection is taking place. Below it will be shown that this condition is important for providing the capability of the detector to suppress the background. The calculations were performed by varying the absolute sizes of the cells, the ratio between the lead weight and the moderator one, the number of counters in the detector at a fixed Pb mass. Fig.2 shows the dependence of the value of the parameter $\langle R^2 \rangle$ on the average thickness of the moderator $\bar{d}$ per one neutron counter. Fig.3 shows ϵ_n as a function of $\bar{d}$ and fig.4 shows the dependence of the ratio $\epsilon_n / \langle R^2 \rangle$ upon the ratio of the volumes of lead V_{Pb}

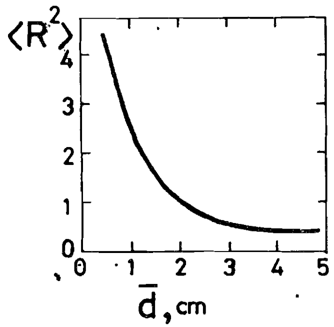

Fig.2. Dependence $\langle R^2 \rangle = f(\bar{d})$, $\langle R^2 \rangle$ in relative units. Each neutron counter weighs 50 kg Pb.

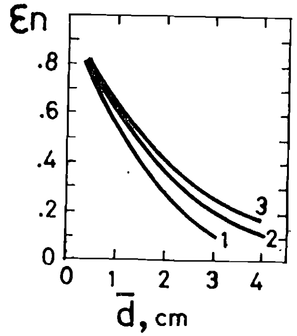

Fig.3. Dependences $\epsilon_n = f(\bar{d})$ for different values of the ratio V_{Pb}/V: (1)$V_{Pb}/V=0.2$; (2)$V_{Pb}/V=0.5$; (3)$V_{Pb}/V=0.75$.

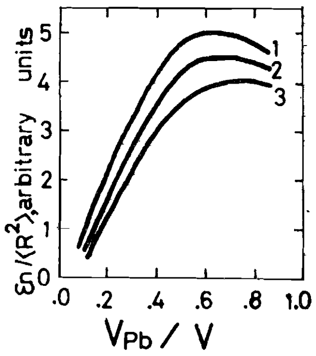

Fig.4. Dependences $\epsilon_n / \langle R^2 \rangle = f(V_{Pb}/V)$ for different Pb mass for each counter: (1) 50 kg, (2) 60 kg, (3) 75 kg.

and the total volume of the detector, V. As is seen from the presented data, with a fixed number of counters in the detector, there exists an optimal ratio between the quantities of lead and moderator material for which the ratio $\epsilon_n / \langle R^2 \rangle$ has a maximum value. A further choice of the detector parameters is determined by the conditions under which the background due to multiple neutron events resulting from cosmic ray interactions is maximally suppressed.

3. Possibilities of suppressing the background

In refs.[6,7,9] it was pointed out that if the experimental setup is installed in an underground laboratory and is protected against charged cosmic ray particles (mostly muons) by an anticoincidence system, there remain two substantial sources of the background: high energy neutrons emitted from the walls, and neutrinos.

The data presented in ref.[7] can be employed for estimating the high-energy neutron flux. To estimate the background from high energy nucleons we calculated the multiplicities and the spatial distribution of the formation points for secondary neutrons generated in the infinite lead block as a result of the interactions of energetic nucleons with the Pb nuclei. The calculation was carried out using the method described in ref.[10]. In fig.5 the numbers of secondary neutrons produced in the interactions of neutrons and protons with Pb nuclei are given as a function of the projectile energy.

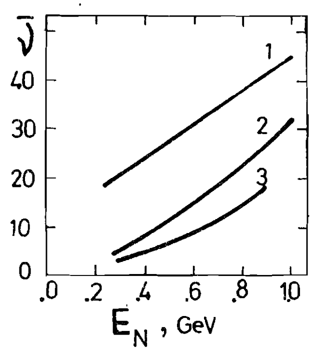

Fig.5. The bombarding energy dependence of the number of secondary neutrons produced in interactions of energetic neutrons (1) and protons (2) with the infinite lead block; (3) data from ref. [11].

As one can see from fig.5, the average numbers of secondary neutrons formed in the interactions of 0.3 GeV $\leq E_n \leq$ 1.0 GeV neutrons and 0.7 GeV $\leq E_p \leq$ 1.2 GeV protons with Pb are comparable with the average number of primary neutrons produced as a result of the oscillation of a bound neutron. Note that in the real geometry of the detector these numbers are somewhat smaller for the interactions of energetic nucleons since a part of the primary particle energy will be lost in interactions with light nuclei, such as ^{12}C, and this will lead to the breakup of the ^{12}C nuclei to α-particles and the emission of few neutrons. Consequently the number of secondary particles will be lower by 10-15% and the ranges of primary neutron and proton energies producing the background events will be displaced toward the higher energies.

As for the interactions of atmospheric neutrinos, it is known [10] that neutrinos and antineutrinos with energies $E \geqslant 0.3$ GeV induce about 0.16 interaction per year per one ton of the detector substance. Of these interactions, there are 0.05 electromagnetic interactions, 0.10 interactions of charged currents and 0.01 neutral currents. It is hardly possible to estimate more or less accurately the number of such neutrino interactions which could lead to neutron events similar, in multiplicity and spatial distribution, to events due to nucleon decay or n − $\bar{n}$ oscillation. Neutrons can be produced not only in neutrino interactions proper, but also in the secondary interactions of nucleons and pions formed in neutrino interactions. According to the data of ref. [13] in the interactions of stopped pions with ^{208}Pb nuclei the average number of secondary neutrons is equal to about 7, and only in a few per cent of cases it reaches 17-20. The neutrino interactions leading to the formation of several slow pions present special danger. In ref. [14] it was found that

the number of the $\nu N \rightarrow l^{\pm} X^{\mp,0}$ interactions of atmospheric neutrinos (where l is a lepton, X = $\pi\pi$ or $\pi\pi\pi$) is rather small (about 0.01 interactions per year per one ton). The data presented in that paper [14] concerning the invariant masses and total momenta indicate that such multipion neutrino events are unlikely to be the source of the background in searches for multiple neutron events induced by the $\bar{n}N$ annihilation process occurring in the lead nucleus. Such a supposition can be set forth for nucleon decay events with a lower probability.

In what follows we shall assume that the multiple neutron event background is due to $E_n \geqslant 0.3$ GeV neutrons reaching the detector through the room walls, and due to neutrino interactions with the detector material leading to the production of a $\geqslant$ 0.3 GeV hadron. We shall estimate the possible degree of discrimination between such events by restricting ourselves to the consideration of the interactions of $\geqslant$ 0.3 GeV neutrons and protons with the detector material. This discrimination can be based on the comparison of the parameters of the spatial distributions of the points of detection of neutrons produced in the indicated processes.

We have done the preliminary calculations of such distributions. They are preliminary in the sense that the coordinates of the points of formation of secondary neutrons were calculated for the interactions of high-energy neutrons with an infinite lead block the density of which was determined as $\rho = \rho_{Pb} (V_{Pb}/V)$, where ρ_{Pb} =11.2 g/cm^3, V_{Pb} and V are the volume occupied by Pb and the full detector volume, respectively. Fig.6 shows the distributions in the Z axis of the formation of secondary neutrons in the interactions of nucleon with an energy E_N = 0.5 and 1 GeV with Pb for the case $\rho = 1/2\,\rho_{Pb}$ (the Z axis coincides with the direction of the momentum of the high-energy nucleon). The distribution of the points of detection of secondary neutrons was constructed with respect to the centre of gravity of the distribution of the formation points by folding with the distribution of neutron detection points which has been obtained for the real detector geometry and the point source of evaporated neutrons.

Fig.7 shows the results of such calculations for one variant of the detector. The difference between the distributions (I) and (2) gives the degree of background suppression compared with the spatial pictures of the processes of nucleon decay or neutron oscillation in the nucleus (I) and of the interaction of an energetic nucleon with the detector material (2). The final choice

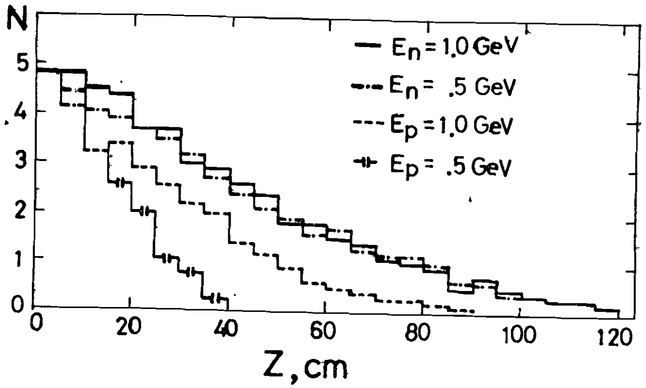

Fig.6. The depth distributions of the points of formation of secondary neutrons in an infinite lead block for different energies of the incident nucleons. N is in relative units. The Z axis coincides with the direction of the motion of the primary nucleon.

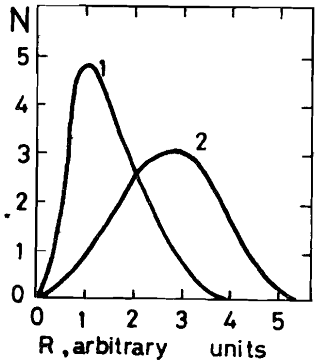

Fig.7. Distributions of the points of detection of the neutrons emitted from a point source (relative to the source) (1), and of those emitted in the interaction of a high-energy nucleon with the detector material relative to the centre of gravity of the formation points distribution for secondary neutrons (2).

of the detector parameters consists in the optimization of the dependences presented by curves in figs.4 and 7. According to the obtained estimates for the "decay" neutrons (i.e., the neutrons emitted in multipion nucleon decay or in antineutron annihilation in a heavy nucleus) a spherically symmetric spatial distribution of detection points should be observed with a width parameter $\langle R^2\rangle \cong$ 250-300 cm^2 depending on the quantity of Pb in the detector cell and on the cell size. For the secondary neutrons produced by the

interactions of energetic nucleons with the detector material, this distribution will have the form of a prolate ellipsoid (with a semiaxis ratio of approximately 2), stretched toward the momentum of the primary particle, the parameter $\langle R^2\rangle \simeq$ 500-550 cm^2 being noticeably larger than that for the "decay" neutrons. In the case of detecting a neutron number of the order $\bar{\nu}\epsilon_n \simeq$ 10-30 in one event, the estimates based on the χ^2 criterion allow one to expect a factor of $\geqslant$ 10 suppression of the background events with a loss of $\leqslant$ 20% of the events of nucleon decay or neutron oscillation.

4. Conclusion

We note that the final estimate of the sensitivity of the method of detecting nucleon decay and the oscillation of neutron bound in the nucleus requires more precise data especially concerning the background conditions of the experiments, for example, the number of the interactions of energetic nucleons and neutrinos at different depths, some data on the multiplicities, momenta and energies of secondary particles involved in neutrino interactions, etc. The construction of a model set-up would make it possible to obtain such information and to verify the calculations performed. The choice of the detector will still require additional considerations but the following variant seems to be possible. The detector may be 1.3 m high and 1.3 m in diameter, the number of ^{3}He-filled counters is 780, the counters are 1.3 m long and 1.5 cm in diameter, the gas pressure is equal to 4 atm, Pb occupies the ⅓ th fraction of the detector volume. Then $\epsilon_n \simeq 0.75$, $\langle R^2\rangle$ = 280 cm^2.

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Оценка параметров установки для поиска распада нуклона и осцилляции нейтрона по множественным нейтронным событиям, детектируемым в массивных образцах

Оценены параметры детектора для регистрации распада нуклона или осцилляции внутриядерного нейтрона по наблюдению множественной эмиссии нейтронов из массивных образцов, проведены расчеты эффективности регистрации и пространственных распределений точек регистрации нейтронов, испущенных из точечного источника для различных вариантов геометрии детектора. Для оценки фоновых характеристик детектора проведены расчеты множественностей и пространственных распределений точек образования вторичных нейтронов, рождающихся при взаимодействиях протонов и нейтронов с энергиями 0,3-1 ГэВ с бесконечными блоками свинца различной плотности. Показано, что сравнение пространственных распределений точек регистрации нейтронов для процесса распада нуклона или осцилляции внутриядерного нейтрона и фоновых процессов позволяет снижать фон детектора более, чем в 10 раз.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Assessment of the Parameters of a Setup for Searches for Nucleon Decay and Neutron Oscillation by Detecting Multiple Neutron Events in Massive Samples

The parameters are assessed of a detector designed for recording nucleon decay and/or the oscillations of a neutron bound in the atomic nucleus by detecting multiple neutron emission events in massive samples. Calculations have been carried out for the detection efficiency and for the spatial distribution of the points at which the single neutrons emitted from a point source had to be detected, for different variants of the detector geometry. To evaluate the background characteristics of the detector, calculations have been performed for the multiplicities and spatial distributions of the points of formation of secondary neutrons occurring in the interactions of 0.3-1 GeV nucleons with infinite lead units. It is shown that the comparison of the spatial distribution of the points of neutron detection for nucleon decay or the neutron oscillation phenomena and the background processes allows one to suppress the cosmic-ray background of the detector by a factor of more than 10.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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