A NEW EXPERIMENTAL LIMIT ON NEUTRON-ANTINEUTRON TRANSITIONS

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An experiment has been set up at the Institut Laue–Langevin in Grenoble to search for free neutron–antineutron oscillations. No candidate events were observed in the first run of the experiment, providing a lower limit in the oscillation time $\tau_{n\bar{n}} > 10^7$ s at 90% CL, which improves the previous experimental limit by an order of magnitude.

1. Introduction

Baryon number non conserving interactions may induce $n \rightleftharpoons \bar{n}$ mixing and consequently $n \rightleftharpoons \bar{n}$ oscillations. Moreover, if the mixing occurs via a first order process through a $\Delta B = 2$, $\Delta L = 0$ interaction, the characteristic oscillation time in the region of $\tau_{n\bar{n}} \simeq (10^7$–$10^8)$ s should signal new physics at the mass scale 10^2–10^3 TeV [1].

The experiment we will describe was designed to detect free $n \rightleftharpoons \bar{n}$ oscillations up to $\tau_{n\bar{n}} \sim 10^8$ s. A first result is reported here where the lower limit for the oscillation time $\tau_{n\bar{n}} > 10^7$ s was set at 90% CL. This result improves by one order of magnitude the previously measured lower limit $\tau_{n\bar{n}} > 10^6$ s at 90% CL [2].

Experimental limits for $\tau_{n\bar{n}}$ have also been derived in proton-decay type experiments through measurements of the nuclear lifetime ($\tau_{n\bar{n}} > 10^8$ s) [3]. However the evaluation of $\tau_{n\bar{n}}$ from these measurements rests on nuclear model assumptions [4] and it has been noted that the strength of the $n \rightleftharpoons \bar{n}$ transitions need not be the same for free neutrons or neutrons bound in nuclear matter [5], so that $\tau_{n\bar{n}}$ may be determined in a model independent way only by searching for $n \rightleftharpoons \bar{n}$ oscillations with free neutrons.

According to the $\Delta B = 2$, $\Delta L = 0$ interaction, an initially pure neutron state will transform in time and acquire an antineutron component with probability $P(\bar{n}, t)$

$$P(\bar{n}, t) = \frac{\delta m^2}{\delta m^2 + \Delta E^2} \sin^2((\delta m^2 + \Delta E^2)^{1/2} \cdot t), \qquad (1)$$

where $\delta m = (\tau_{n\bar{n}})^{-1}$ is the $n \rightleftharpoons \bar{n}$ transition energy, and $2\Delta E$ the energy gap between the n and $\bar{n}$ states due to external field perturbations. In nature $(\delta m/\Delta E)^2$ is always very small and according to eq. (1) the $n \rightleftharpoons \bar{n}$ transition probability is strongly suppressed. However, $n \rightleftharpoons \bar{n}$ transitions develop in time as t^2,

$$P(\bar{n}, t) = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2 \quad (t \ll \tau_{n\bar{n}}), \qquad (2)$$

up to time t such that the "quasi-free" neutron condition

$$\Delta E \cdot t \ll 1 \qquad (3)$$

is satisfied [6].

In practice experiments try to detect the number of antineutrons $N(\bar{n}, t)$ in an initially pure neutron beam after a "quasi free" flight time t in a region adequately free from all kinds of perturbing interactions: the "quasi free" neutron condition is satisfied when $t = 0.1$ s if the residual gas pressure is $p < 10^{-2}$Pa and the residual magnetic field $B < 10$ nT.

The annihilation event signature will be the typical release of ~ 2 GeV shared among several pions (5 on average) with zero total momentum. The $\bar{n}$ amplitude growth can however be suppressed as B^{-2} by the application of an external magnetic field B, so as to verify the validity of any observed signal.

Background for this type of experiment is essentially due to neutral cosmic ray interactions within the target that simulate an $\bar{n}$ annihilation event; their expected rate is proportional to the target mass and depends on the detector quality.

2. The experiment

The experiment was carried out using the 57 MW high flux reactor at the Institut Laue–Langevin (ILL) in Grenoble. The experimental set-up is sketched in fig. 1.

2.1. The neutron beam and the "quasi free" propagation region

In the experimental set-up cold neutrons moderated in liquid deuterium at 27 K, were transported from a position close to the reactor core to the experimental area through the H 53 channel, a system of totally reflecting neutron guides 60 m long, 6×12 cm^2 cross section, slightly bent so as to eliminate all γ's and fast neutrons coming directly from the reactor. The beam intensity was 2×10^{11} n s^{-1} with a mean wavelength $\lambda \simeq 6.5$ Å corresponding to an energy of 2×10^{-3} eV and a velocity of 600 m s^{-1}; the average neutron divergence being $\theta \simeq 6$ mrad (see fig. 2) [7].

At the exit of the H 53 guide the neutrons enter a 94.5 m long drift vessel which was evacuated to a pressure of 2×10^{-3} Pa. The vessel is subdivided into two contiguous parts. The first part, an inox cylinder 81 m long, 1.2 m diameter and 0.5 cm thick, is used as the "quasi free" propagation region. The second part, 1.4 m diameter, consists of an Al tube 5.6 m long and 0.8 cm thick, which contains the target in its central cross section and is surrounded by the detector, followed by a 7.8 m long inox tube. This is closed at its end by a 2.5 cm thick inox disk whose inner part is covered with a ^{6}LiF layer 0.4 cm thick which acts as a neutron beam dump.

The two parts of the drift vessel are both out of axis in the vertical direction with respect to the H 53 neutron beam guide axis, by 6.7 cm and 9 cm respectively, in order to take into account the fact that neutrons fall due to gravity.

Then, in order to avoid the beam cross section becoming too large, an optical horn focussing system was constructed exploiting the neutron reflection properties within a guide. It consists of a straight divergent guide, made of 32 elements, each 1 m long, whose reflecting walls make an angle $\delta = 3$ mrad with the beam axis. Thus the beam divergence is reduced by a factor 2.5 on the average.

Beam shape and intensity at the target were determined through gold foil activation measurements in several positions along the beam drift path and at the beam stop. The neutron beam was fully contained within the target area and its intensity was evaluated to be $I = 1.3 \times 10^{11}$ n s^{-1} through a MC simulation [8].

The magnetic field in the "quasi free" propagation region was reduced to a value $B < 10$ nT by a passive μ metal shield 76.5 m long, 1.10 m diameter, installed coaxially inside the drift vessel together with an active shield outside the vessel all along the "quasi free" propagation region [9]. The resulting external perturbation energy ΔE was less than 6×10^{-22} MeV for all neutrons.

The effective neutron oscillation time, from their last reflection on the divergent guide to their exit from the "quasi free" propagation region, was evaluated taking into account the neutron energy and divergency distributions and turned out to be $\langle t_1^2 \rangle^{1/2} = 0.037$ s inside the divergent guide and $\langle t^2 \rangle^{1/2} = 0.105$ s in total. The "quasi free" neutron condition was thus satisfied.

During the experiment the residual pressure and magnetic field and the neutron flux were continuously monitored and their values recorded. The magnetic field was measured twice a day all along the beam line.

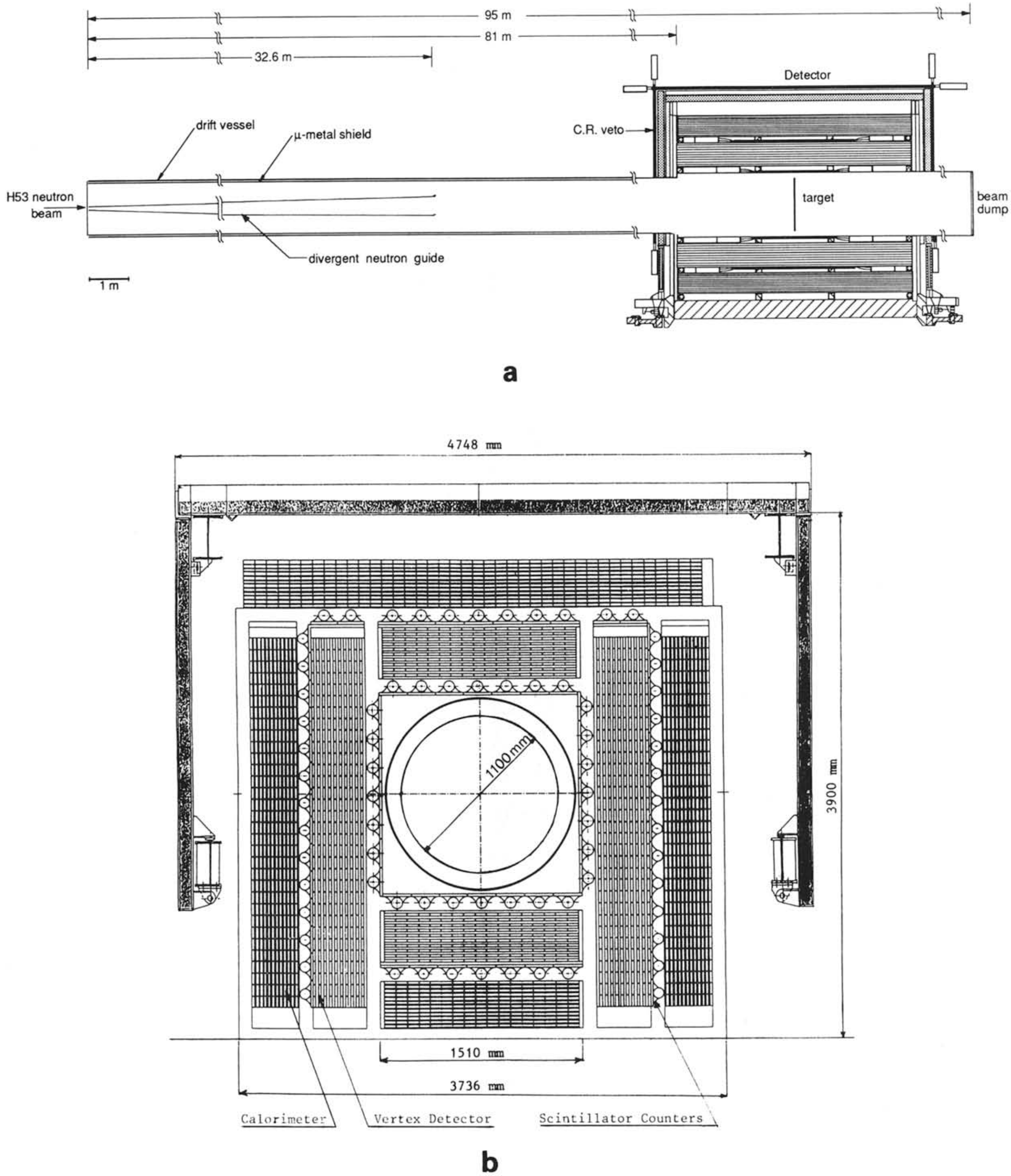

Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

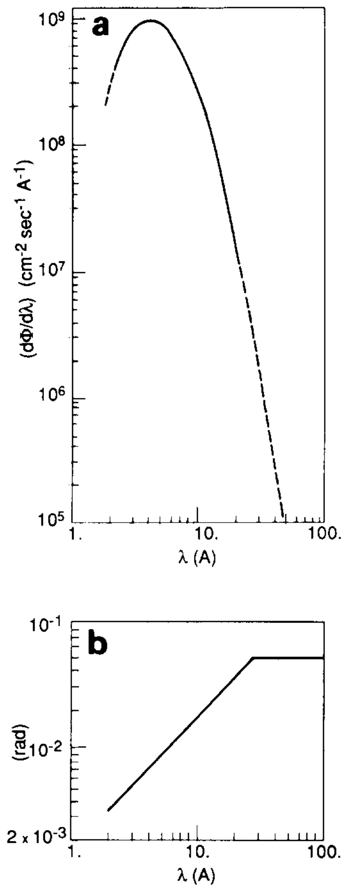

Fig. 2. H 53 neutron beam spectrum (a) and divergence (b) as a function of λ.

2.2. The target and the detector

The target was a C foil 200 μm thick, 110 cm diameter, suspended in the central part of the Al drift vessel (140 cm diameter). It was characterized by a large annihilation probability for a possible n̄ component (>99%) [10], a low Z so as to preserve the peculiar features of the annihilation events, a high transparency to the n beam and a very small mass (~300 g). A ^{6}LiF layer 2 mm thick lining the inner wall of the Al drift tube absorbs the neutrons scattered by the target. The n beam is then dumped into the ^{6}LiF dump 10.8 m after the target.

The n̄ annihilation detector is a tracking device which consists of limited streamer tube (LST) [11] planes and scintillation counter (SC) plates. It is organized in four quadrants and surrounds the target covering a solid angle $\Delta\Omega/4\pi=0.94$. Each streamer tube has a cross section of 0.9×0.9 cm^2, is 5 m long and has a two-dimensional digital read-out.

The inner part of the detector, the vertex detector, is made of 10 planes of LST supported by 10 Al honeycomb plates 2.0 cm thick with average density $\rho=0.3$ g cm^{-3}. The vertex detector is sandwiched between two layers of SC 2 cm thick, 21 cm large, 55 cm apart, which cover a solid angle $\Delta\Omega/4\pi=0.8$ around the annihilation target. The inner SC are 210 cm long, the outer ones 300 cm long. The charged tracks crossing this part of the detector are well measured and the event vertices are reconstructed better than ±3 cm in each coordinate. Furthermore the time of flight recorded between the SC planes gives the track direction (the time of flight resolution was found to be ±700 ps by measurements of cosmic muons).

The calorimetric part of the detector is placed behind the external scintillator layer and consists of 6+6 LST planes alternating with, respectively, 1 mm and 2 mm thick Pb plates fitted between two 2.5 mm thick Al plates for a total of ~4 radiation lengths. It allows the detection and measurement of γ's from π^0 and provides an estimate of the total energy and momentum associated to the events.

2.3. The cosmic ray shield and veto

The whole apparatus is shielded against charged cosmic rays by an array of 235 plastic scintillation counters covering a total area of 115 m^2. Measurements of the overall efficiency of the veto system showed that it was greater than 0.98. All the SC are equipped with two phototubes and their signals are processed through a mean timer [12] especially designed in order to minimize the signal width and the experiment dead time. Furthermore, to shield the apparatus against neutral cosmic rays as well as to prevent possible antineutron events being rejected by self-veto, 10 cm of lead canned into inox boxes are disposed between the calorimeter and the veto counters.

2.4. Data taking and results

During the final setting up it was possible to run the experiment for a time $T=6.11\times10^5$ s with the "quasi free" condition satisfied with an efficiency $\eta=0.94$ on average.

The parameter

$$\eta=\frac{P(\bar{n},t,B_{\rm eff})}{P(\bar{n},t,B=0)}$$

$$=1-2t^{-2}\int_0^t\int_0^t \mathrm{sen}^2[\phi(t')-\phi(t'')]\,\mathrm{d}t'\,\mathrm{d}t'',$$

where $\phi(t')=\int_0^{t'}\mu B\,\mathrm{d}t$, took into account magnetic field instabilities and inhomogeneities [13]. During this part of the experiment $\eta>0.9$ was required. Moreover, due to residual beam associated noise in the detector, the trigger required at least two charged tracks crossing two different quadrants, i.e. two coincidences between inner and outer SC and at least 4 out of the 10 LST planes in the vertex detector firing at the same time, in anticoincidence with the veto system. A typical recorded event is shown in fig. 3.

The measured trigger rate was 1.5 Hz. The contribution due to accidentals and to charged cosmic rays escaping the veto was determined through an off line analysis of the recorded data to be 0.25 Hz and 1.05 Hz respectively. The accidental rate with a less restrictive trigger was very high, i.e. it was ~200 Hz requiring at last one charged track crossing a vertex detector quadrant. The 0.2 Hz rate remaining after CR and accidental subtraction was found to be well comparable with the neutral CR interaction rate in

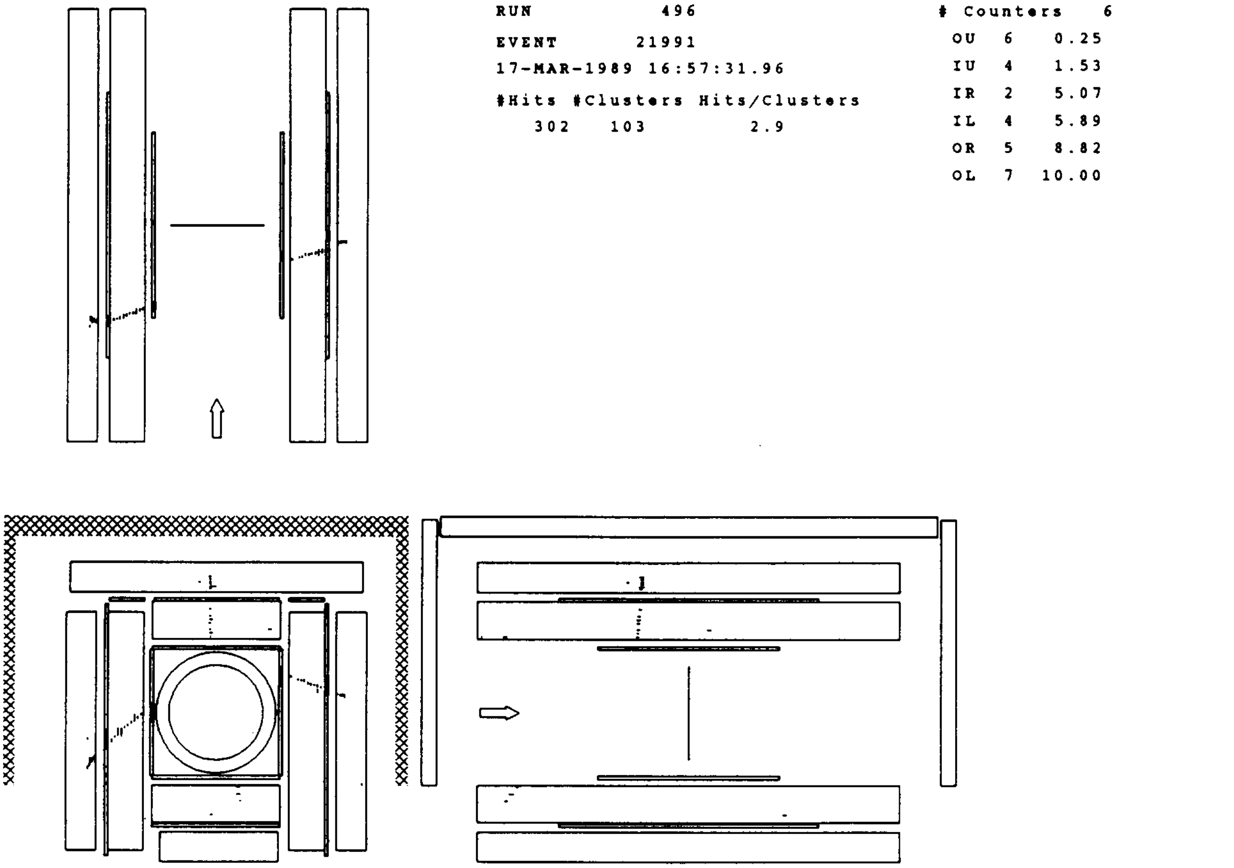

Fig. 3. A typical recorded event. The three orthogonal projections are shown. The black areas on the drawing represent the hitted scintillator counters in the projection orthogonal to the beam axis and the evaluated track crossing point in the scintillators in the other projections. Reported are also the recorded crossing times of the scintillators for the time of flight analysis (I, O for inner, outer sectors; L, R, U, D for left, right, up and down).

the apparatus, as measured during beam-off runs.

The event selection was based entirely on the reconstructed vertex in the target and consistency with the track time of flight.

According to the antineutron annihilation peculiarities a simple algorithm was developed and candidate events were selected according to the following conditions:

(a) number of hits (N_h = number of signals picked up from the streamer tubes)

$$N_h \geqslant 150.$$

This selection criterion approximately corresponds to the requirement of an energy deposition in the detector > 500 MeV, as was derived from detailed measurements of charged and neutral cosmic ray events. 95% of the 0.2 Hz original sample survived this cut.

(b) The event tracks are expected to be directed from the central part of the detector outward; thus events were rejected when a scintillator counter in the outer SC layer in the upper part of the apparatus was firing at least 1 ns before the other ones. A track defined by at least 4 LST planes before and after the SC plane was required in coincidence. The track had to cross the SC in the area defined by the reconstructed coordinate in the SC, 35% of the reduced sample survives this cut.

(c) Events were rejected when the activated SC were all in one side of the detector with respect to the center of the target (left or right, upward or downward). 70% of the remaining events survives this cut, giving a final rate of 0.05 Hz or ~4000 events per equivalent running day.

The selected events were visually inspected searching for events with $N_h \leqslant 600$ (corresponding to a total energy deposition of ~2000 MeV), at last 3 tracks converging in the target region (±50 cm each side in the beam direction) and showing coherent times of flight with the reconstructed event vertex position. Furthermore events were rejected when the tracks, in the projection perpendicular to the beam, were all inside an angle $\theta < 180°$.

The selected events have been measured: no event was found satisfying the final requirement according to which the reconstructed event tracks were required to meet in the target within the loose condition $r < 55$ cm and $|z| \leqslant 10$ cm, where r is the distance of the vertex from the beam axis and z its distance from the target along the beam axis direction.

In order to determine the efficiency ϵ for antineutron annihilation detection in the experiment, antineutron annihilation events generated in carbon nuclei through a MC were passed through a detector simulation which included effects of energy loss, gamma materialization, multiple scattering, interactions and decays in the vacuum pipe and in the detector [14]. The simulated events, analyzed by the same program used for the analysis of the data, allowed the determination of the antineutron annihilation detection efficiency ϵ in the experiment. It turned out that $\epsilon = 0.40 \pm 0.02$ where the error is systematic.

The experimental data are summarized in table 1. From these data and eq. (4) the lower limit $\tau_{n\bar{n}} > 10^7$ s at 90% CL was derived. This result improves the previous experimental limit by one order of magnitude and establishes the upper limit $\delta m < 6 \times 10^{-29}$ MeV at 90% CL for the $n \rightleftharpoons \bar{n}$ transition energy.

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Table 1
Experimental data.

neutron intensity I	$I = (1.3 \pm 0.2) \times 10^{11}$ n s^{-1}
neutron "quasi free" propagation time t	$t = 0.105 \pm 0.004$ s
effective running time T	$T = 6.11 \times 10^5$ s
"quasi free" condition efficiency η	$\eta = 0.94 \pm 0.02$
trigger rate R	$R = 1.5$ Hz
neutral trigger rate R_N	$R_N = 0.2$ Hz
annihilation event detection efficiency ϵ	$\epsilon = 0.40 \pm 0.02$
number of candidate events $\bar{N}$	$\bar{N} = 0$

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