NEUTRON-ANTINEUTRON OSCILLATIONS

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Résumé - Le projet de la nouvelle expérience à l'ILL pour la détection de τosc jusqu'à 2 \times 10^8 secondes est discuté d'après les résultats expérimentaux déjà obtenus à Grenoble.

Abstract - The project for the new Grenoble experiment aiming at detecting τosc up to 2 \times 10^8 sec is discussed on the basis of the experimental results already obtained at the high flux reactor in Grenoble.

INTRODUCTION

With the successful outcome of electroweak unified theory \(^{(1)}\) a new fundamental step has been accomplished toward the general aim of physics, the finding of deeper unity and simplicity in the laws of Nature. At present, the search for grand unified theories appears to open (in a gratifying accord with cosmology) new interesting possibilities, as the question of nuclear matter stability and the determination of neutrino masses \(^{(2)}\).

In the general frame of the unified theories, an appropriate six-quarks coupling might exist, leading to ΔB=2 transitions in nuclei, namely the processes (np)→π(p)^{3}. According to this hypothesis, there must be a ΔB=2 neutron-antineutron mixing, characterized by a mass splitting \(^{(4)}\):

\[ δm = \langle n|H|n⟩ \sim \sqrt{\Gamma \cdot M} \]

where \(\Gamma\) is the ΔB=2 decay rate and \(M\) is the nucleon mass.

An interesting consequence of this assumption is that an initially pure neutron beam becomes a neutron-antineutron mixture after a finite time, and neutron oscillations arise with the characteristic transition time

\[ \tau_{osc} = (δm)^{-1} \]

In this context it should be noted that the n-n oscillation process depends on the ΔB=2 coupling constant to the first order: so that \(^{(4)}\) one would expect \(\tau_{osc} \sim 10^6\) sec if \(\tau_{decay} = 10^{10}\) years: the experimental search for neutron oscillations appears then as an excellent means to investigate the existence of ΔB=2 processes.

Actually the theoretical models leave a rather large incertitude in the value to be expected for \(\tau_{osc}\). The so-called "left-right symmetric" models, however, suggest mainly for the neutron oscillation time a value \(\tau_{osc} \sim 10^7\) sec \(^{(5)}\).

Moreover, in the quark-lepton picture the simplest term in the effective Lagrangian that can induce ΔB=2 processes is

\[ L_{eff} \sim M_x^{-5} (qqq^*qqq) + h.c. \]

and therefore, if neutron-oscillation processes are observed in the experimentally accessible region up to \(\tau_{osc} \sim 10^8\) sec, this will open a new physics in the mass range \(M_x \sim 10^3-10^6\) GeV. \(^{(6)}\)
In the following, I will first briefly consider the neutron-oscillation phenomenology and subsequently discuss the experimental problem of the search for $n\rightarrow\bar{n}$ oscillations, with a special emphasis on Grenoble experiment and its perspectives.

**NEUTRON OSCILLATION PHENOMENOLOGY**

The $AB=2$ interaction produces a mixing among neutron and antineutron states, so that $n$ and $\bar{n}$ are no more "two distinct states", but belong to "one two state system" whose time evolution (in the c.m.s.), assuming CP invariance and neglecting decays, is governed by the equation

$$\frac{d\psi}{dt} = -i M \psi ; \quad \psi = \begin{pmatrix} \psi_n \\ \psi_{\bar{n}} \end{pmatrix}$$

with

$$M = \begin{pmatrix} M & \delta m \\ \delta m & M \end{pmatrix}$$

where non diagonal terms represent the $n\leftrightarrow\bar{n}$ transition energy, while diagonal terms the effective neutron and antineutron masses: $M = m + V, \bar{M} = m + V$, $m$ is the neutron(antineutron) mass, and $V, V$, the nuclear and/or electromagnetic potential for neutrons and antineutrons in the surrounding medium.

To the eigenstates of eq. (2)

$$n_1 = \cos \theta \, n + \sin \theta \, \bar{n} \quad n_2 = -\sin \theta \, n + \cos \theta \, \bar{n}$$

belong the masses

$$m_{1,2} = \frac{1}{2} (M+\bar{M}) \pm \sqrt{\delta m^2 + \Delta E^2}$$

where

$$\tan 2\theta = \frac{\delta m}{\Delta E} \quad \text{and} \quad \Delta E = \frac{1}{2} (V - V)$$

The time evolution of a neutron state

$$n = \cos \theta \, n_1 + \sin \theta \, n_2$$

is described by the equation

$$n(t) = \cos \theta \, n_1 e^{-m_1 t} + \sin \theta \, n_2 e^{-m_2 t}, \quad \text{and the probability of finding an antineutron component at time t, in a state that at t = 0 was a pure neutron state, is given by}$$

$$P(n, t) = \left(\frac{\delta m}{\Delta M}\right)^2 \sin^2 (\Delta M t)$$

Eq. (4) shows that the probability $P(n, t)$ oscillates with amplitude $A = (\delta m/\Delta M)^2$ and angular frequency $\omega = \Delta M$, where

$$\Delta M = \frac{1}{2} (m_1 - m_2) = \sqrt{\delta m^2 + \Delta E^2}$$

Free and quasi Free Neutrons

In the case of free neutrons the $n\rightarrow\bar{n}$ energy splitting $\Delta E$ is equal to zero and eq. (4) reduces to the equation
or simply to

\[ P(\bar{n}, t) = \sin^2 (\delta m \cdot t) \]

when actually observable times \( t \ll \tau \) are considered.

The antineutron component in a free neutron state builds-up as the square of the time.

Moreover, eq. (5) shows that any experiment looking for neutron oscillations will require a very large number of neutrons: if \( \tau \approx 10^7 \text{sec} \), an initial number of at least \( 10^{16} \) neutrons are needed in order to produce a \( n \rightarrow \bar{n} \) transition within a time interval \( t \approx 0.1 \text{sec} \).

In practice, neutrons are never free, \( \Delta M \) is much larger than \( \delta m \), and neutron oscillations are strongly suppressed, the probability \( P(\bar{n}, t) \) going to zero as \( (\delta m/\Delta M)^2 \).

However, real neutrons behave as free neutrons for values of \( t \) and \( \Delta M \) such that

\[ \Delta M \cdot t \ll 1 \]

Eq. (6) represents the "quasi free neutron condition": by it \( P(\bar{n}, t) \) still grows as \( t^2 \), while for \( t > (\Delta m)^{-1} \), \( P(\bar{n}, t) \) oscillates between \( (\delta m/\Delta M)^2 \) and 0 with the angular frequency \( \omega = (\Delta M)^{-1} \).

Thus in order to reach an appreciable value for \( P(\bar{n}, t) \) it is imperative to make \( \Delta E \) as small as possible.

This condition can be fulfilled primarily using neutron beams propagating in a region properly evacuated (in order to avoid nuclear interactions) and shielded against any external magnetic field.

It appears experimentally possible, for example, to reach propagation time \( t \approx 1 \text{sec} \), if the neutron beam propagates in vacuum, in a region where proper shielding reduce the earth magnetic field, \( (\Delta E \approx 10^{-16} \text{MeV}) \), by a factor \( >10^5 \).

Summarizing the above discussion we may conclude that an experimental search on neutron oscillations requires at first:

i) a very intense neutron source;

ii) a propagation region free from any kind of interactions.

**Neutrons in Nuclear Matter**

Since the condition i) is largely satisfied in the deep underground experiments searching for \( \Delta B=1 \) nucleon decays, the possibility has been explored(8) that the same experiments might also detect \( n-\bar{n} \) oscillations in nuclei, thus allowing a measurement of the interesting parameter \( \delta m = (\tau_{\text{osc}})^{-1} \).

The argument may be summarized as follows. In the case of neutrons in nuclei \( \Delta E \) may be evaluated to \( 10^2 \pm 10^3 \text{MeV} \): from eq. (4), for \( \delta m < 10^{-7} \text{MeV} \), it follows that neutrons in nuclei would oscillate with an amplitude \( A < 10^{-6} \) and an angular frequency \( \omega \approx \Delta E \approx 10^{25} \text{sec}^{-1} \).

The effect of neutron oscillations would thus result, in a rough approximation, in an antineutron state in nuclei with a "quasi constant" probability

\[ P(\bar{n}) \approx \left( \frac{\delta m}{\Delta E} \right)^2 \]

which, considering the \( \bar{n} \) annihilation cross-section, \( \sigma \approx \Delta E \), would give rise to annihilation events at a rate \( \Gamma_{\text{ann}} \approx (\delta m/\Delta M)^2 \cdot \Delta E \).

From proton-decay type experiments it resulted \( \Gamma_{\text{ann}} \approx 10^{-31} \text{years} \) (9). These results, due to the presence of unavoidable background effects, appear to be the experimental limit of the present generation experiments.

Moreover, as it is well known, there are substantial uncertainties in relating
free and bound $n\bar{n}$ mixing arising from uncertainty in the $\bar{n}$ optical potential. Furthermore, it has been pointed out recently \cite{10} that the strength of $n \leftrightarrow \bar{n}$ transitions needs not to be the same for neutrons isolated or contained in nuclear matter, and consequently $\Gamma_{\text{ann}}$ does not constrain the value of the free neutron oscillation time.

NEUTRON OSCILLATION EXPERIMENTS

Following the neutron oscillations assumption, a state initially composed of pure neutrons should become, within finite time, a mixture of neutrons and antineutrons. In order to test this hypothesis, one has to detect the antineutrons bringing them to annihilate in nuclear matter.

The antineutron signature will be typical energy release of $\sim 2$ GeV, distributed over several pions (5 in average) with total momentum $p$. Once the "quasi free condition" is satisfied, the constraint which defines the quality of a neutron-oscillation experiment may be deduced from eq. (5) as

$$\tau_{\text{osc}} = \frac{\sqrt{N \cdot \varepsilon}}{I \cdot t_{\text{osc}}} \cdot \frac{E}{v} = \left( \frac{I \cdot \varepsilon \cdot A}{E} \right)^{1/4}$$

where: $I$, the neutron current in $n \text{ sec}^{-1}$, depends on the power of the neutron source; $\varepsilon$, the fraction of annihilation events which can be unambiguously identified, depends on the properties ("quality") of the detector; $t_{\text{osc}} = \frac{L}{v}$, is the time in sec of the "quasi free propagation"; $v$, the neutron velocity in $\text{m sec}^{-1}$; $N \cdot \varepsilon$, for a given source, depends upon neutron energy and annihilation target area.

An important peculiarity of $n\bar{n}$ oscillation experiments carried out with neutron beams lies in the fact that the background can be measured directly. The background is mainly due to neutral cosmic rays interactions that the detector would not be able to discriminate from annihilation processes. However, the antineutron yield may indeed be suppressed at will by a magnetic field $B$ applied in the propagation region (see eq. 4) leaving the cosmic ray background to be measured separately.

THE GRENOBLE EXPERIMENT

The Grenoble experiment was planned in 1980 as an exploratory search, without a special emphasis on sensitivity, but with the definite purpose of singling out the main factors to play upon in planning an experiment apt to reach an actually significant sensitivity in $\tau_{\text{osc}}$. The experimental result obtained \cite{11}

$$\tau_{\text{osc}} > 10^6 \text{sec} \quad \text{at 90\% C.L.}$$

which so far is the first and only experimental result on neutron oscillations, shows the practical possibility of measuring $\tau_{\text{osc}}$ up to $10^8 \times 10^9 \text{sec}$. In the following, I will discuss some details concerning the possibility to raise the present sensitivity by two orders of magnitude.

The experimental set-up is sketched in Fig. 1.

\textbf{a) The Beam.} Cold neutrons were transported to the experimental area along a total reflecting guide (H18) made of 40 elements, each 25 cm long, with $3 \times 20 \text{ cm}^2$ cross-section, arranged on a curve of 25 m radius. The direct radiations from neutron source were that way switched off and, at the same time, the lower energy neutrons were selected: the effective neutron temperature was reduced to $\sim 15^\circ \text{K}$, corresponding to an average velocity $v \sim 160 \text{ m sec}^{-1}$. The beam intensity was $I = 1.5 \times 10^9 n \text{ sec}^{-1}$. Peculiar advantages of this arrangement are:

1) the guide secures a pure neutron beam,
ii) the low neutron velocity contributes directly to the overall sensitivity of the experiment, the measurable limit of \( \tau_{osc} \) being \( \approx \frac{1}{v} \).

b) The Propagation Region. Neutrons propagate under the "quasi free condition" along a straight section 4.5 m long, followed by a vessel 2.7 m long with a diverging conic shape in order to match the divergence of the incoming beam, avoiding collisions on the walls and so conserving the full initial current. The vessel ends on a \(^6\text{LiF}\) target, where the neutrons are dumped. This target, 54 cm diameter, 0.3 cm thick, glued on an Al plate 0.3 cm thick, was supported by an Al disk, 1.4 cm thick, which closed the system into a vacuum tight enclosure protecting the whole propagation region.

The straight guide and the drift vessel were evacuated to a residual gas pressure <10\(^{-5}\) torr, and shielded against the earth magnetic field by a triple \( \mu \)-metal layer, down to \( B \approx 10^{-4} \) gauss.

An auxiliary magnetic field of a few tenth of a gauss, generated by suitable coils, could be switched on along the oscillation region. The average neutron propagation time, from their last collision inside the guide to the \(^6\text{LiF}\) target, was evaluated

\[
t = 2.7 \times 10^{-2} \sec
\]

where

\[
t = \frac{L_o + L_v}{v} > t_v = \frac{L_v}{v}
\]

\( L_o \) being the average free propagation length inside the straight section of the guide and \( L_v \) the length of the actual vessel.

Thus one obtains \( t > t_v \) at a small additional expense.

c) The annihilation Target. Two different approaches have been adopted for the annihilation target. At first the neutron dump itself was used for this purpose. But this solution had an inherent drawback: while the expected annihilations would take place in a very thin layer at the surface of the target, the whole thickness of the \(^6\text{LiF}\) and the Al supporting plates was able to act as a source of background events, which could not be geometrically separated from the true annihilation events.

Therefore as a second solution an almost immaterial target was adopted: a 100 \( \mu \)m Carbon foil which was thick enough to annihilate practically 100\% of the expected \( \bar{n} \) component, still being transparent to the neutrons, was placed 15 cm upstream of the neutron dump.

The neutron beam cross-section at the targets, evaluated on the basis of the guide shape and beam divergence, is shown in Fig. 2: more than 90\% of the expected anni-
Hililation events should lie inside an area of 32x20 cm$^2$ around the center of the annihilation target. It seems worthwhile to underline that the annihilation area required with the described set-up

$$A \propto L_v^2 G^2 < (L_v + L)^2 G^2$$

depends only on $L_v$ and is therefore less than half the area that would be required if the neutrons propagated along the total length $(L_v + L)$ in a divergent vessel. The important point is that detector volume and background effects are proportionally reduced.

Fig. 2 - Lego-plot of the neutron beam at the target.  

Fig. 3 - The calorimeter.

d) The Detector. In the first part of the experiment the main emphasis was on detection of the annihilation energy. The detector (Fig. 3) placed in front of the neutron target acted as a calorimeter: it consisted of 5 modules 16 cm high, 80 cm long, covering an area of 80x80 cm$^2$, each consisting of twenty lead layers and twenty plastic scintillator layers, each 0.5 cm thick. The detector covered a $\Delta \Omega/4\pi \approx 25\%$, of the total solid angle. Successively a fine grain detector was introduced whose major aim was at spatial resolution in order to allow particle identification, track pattern recognition, and vertex reconstruction (see Fig. 1). It surrounded the annihilation target, $\Delta \Omega/4\pi > 0.7$, and consisted of:

- limited streamer tubes (12) (.9x.9 cm$^2$ cross-section) arranged in planes (1x1.5 m$^2$), interleaved with Al or Fe plates, 0.5 cm thick. Each tube plane provided two coordinates for any crossing particle;
- layers of scintillation counters inserted between the metal shields, in front and between the limited streamer tube planes.

Fig. 4 shows two typical events: the vertex reconstruction has an average resolution of a few cm$^3$.

e) The Cosmic Ray Veto System. The whole apparatus was shielded against cosmic rays by means of anticoincidence counters, covering an area of about 30 m$^2$. The overall efficiency of the anticoincidence system was measured to be greater than 99.95%. No shielding material was placed outside, in order not to overload the floor of the experimental hall.

f) Collecting Data. Data were taken alternating 24 hours runs with magnetic field off
Fig. 4 - Two typical events as seen on the display.

(quasi free condition) and with magnetic field on (which depresses the oscillation probability by a factor $\approx 10^6$). Control runs were also made with reactor off.

g) Experimental Results. The experiment may be subdivided in three phases.

- **Phase 1:** $^6\text{LiF}$ target as annihilation target and calorimeter as detector.
- **Phase 2:** $^6\text{LiF}$ target as annihilation target and tracking detector.
- **Phase 3:** Carbon foil target and tracking detector.

For each phase the three sets of experimental data, collected in the three conditions field off, field on and reactor off, were analyzed and compared. The results turned out to be identical, so leading to the conclusion that there was no evidence of neutron oscillations. Furthermore:

1) in phase one, where the energy was detected primarily, possible background and noise from reactor and neutron associated radiation have been considered in detail, with the conclusion that, in our conditions, they are negligible. The total effective running time was $\approx 45$ days equally distributed in the three conditions;

2) in phase two, data were taken during 110 days effective time, 45 "field-off". The collected data, visualized on a display, were scanned for possible annihilation events. In order to have good identification, events with

   a) three or more tracks, at least one in backward and one in forward direction, the latter traversing at least 8 tube planes;

   b) the vertex in the annihilation area within the experimental resolution,

   were selected.

   A candidate event was found, well compatible with the expected background $N_B = 1.8 \pm 0.4$ events.

   A careful study of cosmic ray interactions satisfying the above topological selection criteria was done. Events with vertex inside a cylinder, 10 cm long, starting from the full target area, $\approx 20$ kg in mass, were considered.

   The background event rate was so experimentally determined to be less than 1 event per kilogram of target mass per $10^7$ sec running time;

3) during phase three, in order to avoid background events from cosmic ray interactions in the matter adjacent the target, the annihilation target was moved 15 cm upstream the neutron dump. No further candidate was found in $\approx 65$ days of effective running time. In phase three, indeed, on the basis of phase two results, less than 0.1 background event with the vertex in the C annihilation target was expected during the
complete data taking.
Adding up the results from phase two and three we obtained as antineutron yield
\[ R = \frac{N}{N_0} = \frac{2.3}{1.5 \cdot 10^9 \cdot 10^7 \cdot \varepsilon} = 6 \cdot 10^{-16} \quad \text{at 90% C.L.} \]

where \( \varepsilon \), the effective detection efficiency, resulted \( \varepsilon = 0.27 \) from a Monte Carlo calculation based on experimental data from a test run in an antiproton beam at CERN PS.

Some comments may be appropriate at this point:

i) The cosmic-ray background (which was measured to be less than 1 event per kg target mass, per \( 10^7 \) sec) can be eliminated using a thin isolated target and a detector ensuring good vertex reconstruction and energy resolution.

ii) A limited streamer tube detector appears well suited to provide these conditions.

iii) A cold neutron beam propagated in a slightly bent guide contributes very considerably the efficiency of the system.

THE PROPOSED GRENOBLE EXPERIMENT

The next step we are proposing for the Grenoble experiment aims at measuring \( \tau_{\text{osc}} \) up to \( \approx 10^8 \) sec. It is based on the general considerations discussed above:

a) a cold neutron beam transported to the experimental area by a curved guide and then propagated in the quasi free condition;

b) a thin isolated annihilation target;

c) a fine grain detector with high spatial and energy resolution;

d) an efficient cosmic ray shield.

It will take advantage of the new cold source and a specially designed new neutron guide.

Furthermore, a simple device is envisaged, based on neutron reflection properties within a guide (14), in order to keep dimensions of the annihilation target and the experimental apparatus within reasonable values.

This device consists of a guide with slightly divergent walls which allows somehow to focus (or actually to parallelize) the neutron beam, so reducing its cross-section at the target as shown in Fig. 5. While the glancing angle of a neutron trajectory at the walls of a parallel sided guide remains constant all along, and the same happens for its angle \( \Theta \) with the axis of the guide, a reflection at the walls of a divergent guide reduces \( \Theta \) by \( 2\delta \), where \( \delta \) is the divergence of the walls. So, if \( \Theta_{\text{in}} \) indicates the divergence of a neutron entering the guide, the divergence of the neutron at the exit after \( n \) reflections, will be

\[ \Theta_{\text{out}} = \Theta_{\text{in}} - 2n\delta. \]

The required target area \( A \) needed to contain the beam will be correspondingly decreased by a considerable factor.

On the basis of the experience acquired in the previously described experiment, a new experimental set-up has been designed, as described in the following paragraphs and sketched in the Fig. 6.

![Fig. 5 - The neutron beam cross-section at the annihilation target.](image-url)
1) Neutron Beam and Guide. Cold neutrons will be transported to the experimental area by the new guide H 52 (1.60 m long, R = 5000 m). The outcoming beam will contain $3.3 \times 10^{11} \text{n sec}^{-1}$ at an average $T = 15^\circ \text{K}$ and no spurious radiation.

2) Propagation Region. The quasi free propagation region will consist of
   i) a 30 m long straight guide, with a divergence of $3 \text{ mrad}$;
   ii) a divergent vessel $\sim$30 m long, ending with $\phi = 130 \text{ cm}$;

where a gas pressure $P < 10^{-6} \text{ torr}$ and a residual magnetic field $B < 10^{-4} \text{ gauss}$ warrant the quasi free condition.

The average time interval from the last neutron reflection in the divergent guide to the end of the quasi free propagation region will be

$$t = \frac{L_0 + L_v}{<v>} = 0.1 \text{ sec.}$$

3) Annihilation Target. A $\sim$100 $\mu\text{m}$ thick Carbon foil will be placed downstream the magnetically shielded region. The beam cross-section at the target (see Fig. 5) will be $\sim$70x100 $\text{cm}^2$, and the corresponding vessel diameter $\phi = 130 \text{ cm}$.

The important point is that the annihilation target will be far from any other material.

4) Annihilation Detector. It is shaped as a box surrounding the target with a solid angle $\Delta \Omega/4\pi = 1$. The walls of the box will consist of limited streamer tube planes and scintillation counter plates, immediately outside the propagation vessel. The ensemble (see Fig. 6) works as:
   i) a charged particle vertex detector (10 planes in each side) with no material in between;
   ii) a neutral particle vertex detector (10 planes in each side) interleaved with .5 cm Al plates and a .5 cm Pb plate in front;
   iii) a calorimeter able to absorb the whole energy emitted in annihilation processes, consisting of 16 limited streamer tube planes interleaved with Fe plates of increasing thickness.

A Monte Carlo calculation shows that $\sim$80% of the annihilation processes will be fully...
contained in this ensemble and the vertex reconstructed within few centimeters.

5) Cosmic Ray Veto and Shield. The experiment will be protected by proper material against cosmic ray neutrals and by a veto system against charged penetrating particles.

The main characteristics of the planned experiment are summarized in Table I, and compared with those of the already completed Grenoble experiment.

| OLD EXPERIMENT | NEW EXPERIMENT |
|----------------|----------------|
| Neutron Beam   |                |
| I = 1.5 \times 10^8 n sec^{-1} | I = 3.3 \times 10^{11} n sec^{-1} |
| R = 25 m       | R = 5000 m     |
| \langle \beta^2 \rangle = 25 \AA  | \langle \beta^2 \rangle = 8 \AA  |

Propagation Region

1) 4.5 m long straight guide
2) 2.7 m drift vessel
   \( t = 0.027 \) sec

\[ Nt^2 = 10^4 n \sec^{-2} \]

Annihilation Target

1) \( ^{6}\text{LiF} \) dump
2) C foil \( \sim 100 \) \mu m thick

Neutron beam cross-section at the target \( 36 \times 20 \) cm\(^2\)
   vessel \( \phi = 54 \) cm

Detector

Limited streamer tube planes
   + scintillation counter plates
   \((1 \times 1.5) \times 30 \) tube planes
   Good vertex reconstruction

\[ \frac{A0}{4\pi} = 0.7 ; \; e \geq 0.27 \]

Background

\[ N_B < 1 / 10^7 \text{sec} / \text{kg} \]
\[ \tau \approx 10^7 \text{sec} \]

Sensitivity

\[ \tau_{osc} \approx 10^6 \text{sec} \]

As a conclusion we may state that:

a) on the basis of the analysis of the cosmic ray background reported in the previous paragraph, less than 1 background event in \( 10^6 \) sec would be expected. Therefore, the experiment can be run for a year effective time with no background, so to reach a sensitivity in \( \tau_{osc} \) up to \( 2 \times 10^8 \) sec;

b) in this experiment one expects \( \approx 3 \) annihilation events per day if \( \tau_{osc} = 10^7 \) sec, and still 10 events if \( \tau_{osc} = 10^8 \) sec.
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