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EXPERIMENTAL INVESTIGATION ON THE NEUTRON SPIN PRECESSION IN A GRAVITATIONAL FIELD

by

M. FORTE

1972

Joint Nuclear Research Centre
Ispra Establishment - Italy

Physics Division

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Related effects have been investigated in recent experiments, which are shortly reviewed.

In the present work, a possible precession of the neutron spin in the earth gravitation field is investigated, by analyzing the change in the polarization components of a slow neutron beam.

Original experimental methods are presented and, from the preliminary results, an upper limit is estimated for the gravitational precession frequency of a neutron.

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SUMMARY

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KEYWORDS

PRECESSION
NEUTRONS
SPIN
EARTH
GRAVITATION
POLARIZATION
NEUTRON BEAMS
MEASURING METHODS
MEASURED VALUES
FREQUENCY

I. INTRODUCTION

The possibility that both parity (P) and time-reversal (T) (or CP) invariance may be violated in the gravitational interaction has been considered theoretically and it has been suggested that the gravitational potential could then include symmetry violating terms depending on the spin of interacting particles. (+)

According to the interaction form considered in (1), the gravitational potential, for example, of a proton at rest in the earth field is

$$U = m_p \varphi + m_p\, d\, (\vec{\sigma} \cdot \vec{\nabla} \varphi) = m_p \varphi + m_p\, d\, (\vec{\sigma} \cdot \vec{g}\,), \qquad (1)$$

where $m_p \varphi$ is the newtonian potential and d a length characterizing the "gravitational dipole" (analogous of an electric dipole) of the particle.

For $d \neq 0$, the proton spin would have to precess around the direction of the $\vec{g}$ field, with a frequency $\nu_g = 2\, h^{-1}\, m_p\, d\, g$, but, for $d \simeq \hbar / m_p c$ (proton Compton wavelength) the precession would be very slow (with a period of ~ 3 years) and practically unobservable.

In a later paper, by Leitner and Okubo (2), it is shown, by rather general arguments, that, referring to the previous example, the effective potential can be expressed as :

$$U\,(r) = U_0(r) + (\vec{\sigma} \cdot \hat{r})\, U_1\,(r)\ , \qquad (2)$$

(+) For instance, an interaction term $(\vec{\sigma}_1 \pm \vec{\sigma}_2) \cdot r_{12}\, f(r_{12})$ between two particles separated by a distance r_{12}, with $f\,(r_{12})$ a scalar function, is odd both under space inversion ($\vec{r} \to -\vec{r}$; $\vec{\sigma} \to \vec{\sigma}$) and under time inversion ($\vec{r} \to \vec{r}$; $\vec{\sigma} \to -\vec{\sigma}$).

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where r is the distance and $\hat{r}$ an unit radius vector from the centre of the earth. (+)

$U_0(r) = m_p \varphi$ represents the newtonian potential (neglecting an arbitrary constant) and $U_1(r)$ is a function to be determined.

At the surface of the earth, $r = R$, we have

$$U(R) = U_0(R) \left(1 + A \left(\vec{\sigma} \cdot \hat{r} \right) \right) ,$$

where $A = U_1 (R)/U_0(R)$ is a parameter representing the degree of both P and T violation.

In comparison with the experience (no evidence for a gravitational line splitting in the hyperfine structure of hydrogen atom) the authors placed an upper limit $|A| \lesssim 10^{-11}$, concluding that the symmetry violating term could be present in a proton's potential, but only to the extent of one part in 10^{11}.

The search for spin-dependent gravitational effects has been object of recent experimental works, which we shall briefly review.

Most accurate informations can be obtained from nuclear magnetic resonance experiments.

According to the previous assumptions, the NMR frequency ν of a spin 1/2 particle in a gravitational field will be determined by the hamiltonian $\vec{\sigma} \cdot (\mu \vec{B} + \hat{r} \; U_1)$ and values of ν different from $\nu_0 = 2 \mu B h^{-1}$ may be expected accordingly.

When the magnetic field is oriented along the vertical,

(+) In particular, with $U_1 = m_p \, d \vec{\nabla} \varphi$, we have the form (1)

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$\bar{B} \uparrow\uparrow \hat{r}$ or $\bar{B} \downarrow\uparrow \hat{r}$, we have $\nu^{\uparrow\uparrow} = \nu_0 + 2\,U_1\,h^{-1}$ and $\nu^{\downarrow\uparrow} = \nu_0 - 2\,U_1\,h^{-1}$, whereas, when the field is $\bar{B} \perp r$, we find $\nu_\perp \simeq \nu_0$, neglecting terms of the order of $(U_1/\mu B)^2$ or higher.

An apparent dependence of the proton NMR frequency on the orientation of $\bar{B}$ relative to the gravitational field was pointed out in (3). The quoted effect is consistent with some discrepancies between published values of the proton gyromagnetic ratio $\gamma_p = \omega/B$ measured with different experimental dispositions and, likewise, it was shown in an experiment, performed with an orientable NMR device, allowing a direct comparison between the proton resonance frequencies obtained with a vertical and a horizontal orientation of the magnetic field B (in the range 64 ~ 170 gauss).

While no effect of the kind $\nu^{\uparrow\uparrow} \neq \nu^{\downarrow\uparrow}$ was put into evidence, a difference $\Delta\nu = ((\nu^{\uparrow\uparrow} + \nu^{\downarrow\uparrow})/2 - \nu_\perp)$ larger than the errors was found, typically $\Delta\nu \simeq (30 \pm 10)$ cps.

The latter effect, if it exists, in absence of the former, cannot be explained with the interaction hamiltonian previously assumed.

Subsequent experiments (4) (5), failed to show any effect of the kind reported in (3), although much better frequency resolutions widths were reached.

From the results of (4) one may also place an upper limit $\nu_g = (\nu^{\uparrow\uparrow} - \nu^{\downarrow\uparrow}) < 3$ cps (roughly estimated).

We remark, however, that the latter experiments were performed with much lower field intensities, $B < 1$ gauss and, therefore, the so far unexplained results of (3) have not been directly verified.

Aiming to extend the investigation to the case of the free neutron, the neutron magnetic resonance experiments have been considered, first.

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Only the relative values $\gamma_n / \gamma_p = \nu_n / \nu_p$ can be obtained from accurate neutron resonance experiments (6) (7), in which the magnetic field intensity is determined with reference to the proton NMR frequency.

The interpretation of experiments of this kind is no longer straightforward, since the independence of γ_p on the experimental conditions (field orientation and intensity) is under discussion.

Moreover, accurate experiments (known to the author) have been performed with horizontal field only, so that no indication could be found concerning a possible influence of the gravitation on the neutron resonance frequency.

Considering experiments of different kind, it is worth mentioning that the possibility that the gravitational acceleration of the free neutron may have two different values corresponding to the two vertical spin projection was looked for (8) (+), but no splitting in the g value was found, within an accuracy of percent of g .

In the present experimental research we have looked, by a direct method, for a possible precession of the neutron spin around the direction of the earth gravitational field.

From the preliminary results obtained, an upper limit has been estimated for the gravitational precession frequency of a neutron.

(+) In (8), reference is made to a private communication by Wheeler concerning this effect, which was suggested by Spitzer.

According to (2), a difference could be found, for $\vec{\sigma} \cdot \hat{r} = \pm 1$, $(g^+ - g^-) = 2 m_n^{-1} dU_1 / dr$, depending on both the magnitude and the form of U_1.

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II. EXPERIMENTAL METHOD

The experimental set up (Fig. 1) includes :

a) a system producing a longitudinally polarized neutron beam,

b) a neutron path section where the magnetic field is ideally zero and a gravitational precession of the neutron spin can freely take place,

c) a system for analyzing the final neutron polarization.

a) A vertically polarized slow neutron beam is obtained by reflection on a Co-Fe mirror, magnetized in a vertical field gap, installed at a beamhole of the Ispra-I reactor.

After passing in a vertical magnetic guide field, the beam is collimated close to the axis of a tube around which a cylindrical coil is wound.

Starting from the input of the latter, the winding density increases, while the vertical guide field decays, in such a way that a regular rotation of the resulting field ($\gtrsim$ 20 gauss) into the axial direction $\hat{z}$ is performed, in a $\sim$ 20 cm length.

The neutron spins are thus adiabatically turned and a longitudinal polarization P_z is obtained, which can be reversed by reversing the coil current.

Entering then into a coaxial magnetic shield, the coil field is made to decrease exponentially down to $\sim$ 0,5 gauss, so to "guide" the neutron polarization to a successive beam path section, about 40 cm long, protected by two coaxial magnetic shields, where the residual field is almost completely negligible.

b) It is assumed that, here, a neutron spin precession may take place around the vertical direction ($\hat{y}$ axis), with an angular frequency $\omega_1 = 2\hbar^{-1}U_1$, and produce, in a length 1, a small change $P_x \cong \alpha = \omega_1 \Delta t = \omega_1 l \, v^{-1}$

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in the P_x component of the normalized $\overline{P}$ vector.

On the other hand, it is possible to modulate and to attenuate the effect under investigation, by adding a uniform longitudinal field, which can be supplied by a solenoid, 40 cm long, regularly wound around the beam axis (modulation solenoid).

By this method, as described in the analysis of results, the precession effect under investigation can be put into evidence, notwithstanding some eventual systematic zero error in the polarization measurement.

c) The final neutron polarization is analyzed by means of a vertically magnetized mirror similar to the polarizer.

The neutrons pass quickly from the very weak field region into the vertical field (~ 1 gauss) existing inside a coil, having a narrow rectangular cross section.

The vertical field is successively made to increase, by a couple of magnetic guides connected to the magnetic gap of the analyzer.

The effect of such a coil (polarization filter) is to start a sudden precession of the spins around the $\hat{y}$ axis, so that the P_y component only will be conserved and analyzed.

Otherwise, in order to analyze the polarization along the $\hat{x}$ direction (or any chosen direction in the (x,y) plane), the $\overline{P}$ vector is previously made to precess around the $\hat{z}$ axis by a right angle (or the appropriate angle).

The precession is effected around a suitable longitudinal field supplied by a coil (precession coil) placed before the polarization filter.

In order to determine the polarizer-analyzer efficiency product $P_1 P_2$, necessary to normalyze the $\overline{P}$ vector, the

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filter coil can be replaced by another coil forming, in the analyzer guide field, a spin rotator similar to the input rotator.

In this case, a longitudinal guide field between the first and the second rotator can be supplied by feeding the modulation solenoid.

This method gave results for P_1 P_2 in close agreement with the conventional depolarizing shim method.

The neutrons reflected from the analyzing mirror are detected by a BF_3 counter.

Another BF_3 counter viewing a teflon scatterer placed in the beam, before the analyzer, was used as a monitor. (+)

III. MEASUREMENTS AND RESULTS

The polarization component under investigation, usually P_x , was measured by alternating the input polarization with a period of 1 s.

As a normalized value, we have taken $P_x = (A_N - A_M)/P_1\ P_2$, where $A_N = (N_1 - N_2)/N_1 + N_2)$ is the analyzer counter asymmetry and A_M is a correction corresponding to the monitor asymmetry, which, however, was found irrelevant.

The polarization efficiency product, determined from time to time in the course of the measurements, had a constant value $P_1\ P_2 \cong 0,40$.

As previously mentioned, the measurement may be affected by a systematic zero error, largely due to magnetic field misalignement and to stray fields, both in the polarizing and in the analyzing system and, to some extent, to the

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(+) Methods of the kind employed in this work are more exaustively treated in a next report "Methods for the orientation and the analysis of the neutron polarization", by M.Forte (in preparation).

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imperfection of the spin rotator.

However, the zero error in P_x and in P_y , too, appeared smaller than $\sim 3.10^{-2}$.

In each run, P_x was analyzed at various values of the current in the modulation solenoid, for which the magnetic field B_s was calculated (Fig.2).

The point at zero current was repeated a few times throughout the run, with a good statistical accuracy, and no drift in the zero error larger than the statistical error was observed.

Along the path length l , the neutron magnetic precession caused by spurious fields $\overline{B}'$, not completely eliminated by the magnetic shielding, may result to an error

$$\Delta P_x = 2\hbar^{-1}\mu_n v^{-1} \int_0^1 B'_y \, dz \quad .$$

The magnetic shield is submitted to the stray fields (5 ~ 7 oersted) of the polarizer and of the analyzer magnets.

To be sure, the latter have been compensated (within ± 0,5 oersted) by a suitable disposition of permanent magnets, however no significant change in the results was observed (Fig.2), except a slight zero shift.

An error limit estimate was also obtained

$$\left| \int_0^1 B'_y \, dz \right| \lesssim \int_0^1 B'_r \, dz \simeq (0,5 \ . \ 10^{-3} \text{ gauss}).1 \ ,$$

by measuring the intensity B'_r of radial components, by means of a rotating coil magnetometer.

IV. ANALYSIS OF RESULTS

By analyzing the modulation curves (Fig.2), an evaluation of $\omega = \omega_1 \, l \, v^{-1}$ can, in principle, be obtained.

Through the modulation solenoid, the $\overline{P}$ vector will precess, by an angle ε_1 , around the fixed vector $\varepsilon_1 = \varepsilon + \alpha$,

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where $\varepsilon = \omega_s \; l \; v^{-1} \; \hat{z}$ and $\alpha = \omega_1 \; l \; v^{-1} \; \hat{y}$ give the axis and the angle of the $\bar{P}$ vector precession which would be produced, separately, by the magnetic interaction with the solenoid field ($\omega_s = 2 \hbar^{-1} \mu_n B_s$) , and by the gravitational interaction ($\omega_1 = 2\hbar^{-1} U_1$) see Fig.3) .

Under the assumption $\alpha \ll \varepsilon$ and, therefore, $\varepsilon_1 \simeq \varepsilon$, the base of the $\bar{P}$ precession cone is very close to a circle on a (x,y) plane, represented in Fig. 3 b.

It easily seen that the initial polarization $\bar{P}_o (\vartheta_o , \varphi_o) = \bar{P}_{oz} + \bar{P}_{o\perp}$ will turn into $\bar{P}_1 (\vartheta , \varphi)$, with

$$\bar{P}_{1x} = \bar{P}_{o\perp} \cos (\varepsilon + \varphi_o) - (\alpha/\varepsilon) \sin\varepsilon .$$

Adding a constant zero error C, we have finally a form

$$P'_x = P_{1x} + C = - (\alpha/\varepsilon) \sin + P_o \cos (\varepsilon + \varphi_o) + C = F (\varepsilon)$$

which should be fitted with the experimental points at various ε , in order to determine α.

The first term, having the full magnitude of the effect, α , at $\varepsilon = 0$, is largely attenuated for $\varepsilon \gtrsim \pi$.

The sinusoidal term, depending on the misalignement of $\bar{P}_o$, mainly due to the imperfection of the spin rotator, was reduced in amplitude at a sufficiently high current in the rotator coil.

For purpose of calibration, the sinusoidal term was enhanced, by adding a perturbing field near the end of the rotator coil (Fig. 4) .

The agreement of the experimental curve with a form $P_o \cos (\varepsilon + \varphi_o)$, at least for an interval of precession angles ε ($\div B_s$) covering a full period, is sufficiently good to permit a determination of the ratio (B_s / ε)

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useful for our purposes.

The deviations of the curve appearing as the precession angles become larger, are essentially due to a non negligible neutron velocity spread.

We have found $(B_s / \varepsilon) \cong 0{,}20$ gauss rad $^{-1}$.

Incidentally, the neutron velocity can also be obtained, from the relation $(B_s / \varepsilon) = v\, l^{-1} \hbar^{-1} \mu_n^{-1} /2$.

A mean velocity was found $\langle v \rangle \cong 1{,}6 \cdot 10^5$ cm s $^{-1}$, and a mean time of flight across the solenoid $\langle \Delta t \rangle \cong l \langle v \rangle^{-1} \cong 2{,}5 \cdot 10^{-4}$ s.

The present measurements concerning the neutron gravitational precession are preliminary and a better accuracy would be desirable in order to work out a detailed analysis of the modulation curves.

However, by applying a simple criterion, an upper limit estimate for α could be obtained.

Indeed, the oscillation of $F(\varepsilon)$ in the interval $(-2\pi, +2\pi)$ largely satisfies the inequality

$(F_{max} - F_{min}) = \Delta F > 2|\alpha|$, for any value of $P_{0\perp}$ and φ_0.

From the measurements (round points in Fig. 2) we have $\Delta F \lessapprox 1{,}8 \cdot 10^{-2}$ and, taking into account the previously discussed uncertainities concerning the zero point stability and the magnetic precession effect, we have estimated $|\alpha| \lesssim 1{,}25 \cdot 10^{-2}$.

From the relation $\alpha / \varepsilon = \omega_1 / \omega_s$, we get

$\omega_1 = 2\pi \nu_g = 2 h^{-1} \mu_n (B_s / \varepsilon) \cdot \alpha$, and we can set an experimental limit to the spin precession frequency of a neutron in the earth gravitational field $|\nu_g| \lessapprox 8$ cps.

We may also quote an upper limit for the relative magnitude of the P and T symmetry violating term which could be present in the gravitational potential of a free neutron, referring to the form considered in section **I** :

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$$|A| = |U_1(R)/U_0(R)| = (h\gamma_g/2)/(m_n R g_0) \lesssim$$

$$\lesssim (2,5.10^{-26}\ \text{erg})/(1,05.10^{-12}\text{erg}) \cong 2,5.10^{-14}$$

In conclusion we note that the limits achieved with the present method are comparable with the quoted proton NMR experiments.

Substantial improvements seem possible, after the gained experience.

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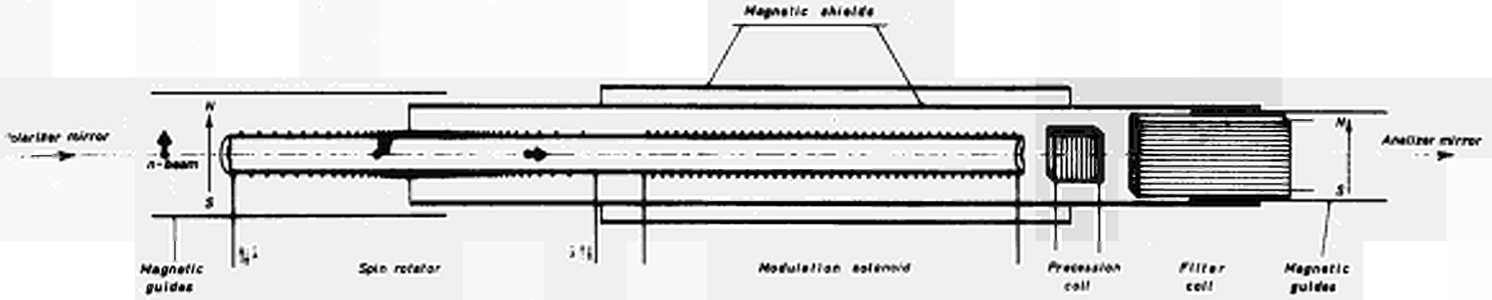

FIG. 1 - Scheme of the experimental set up

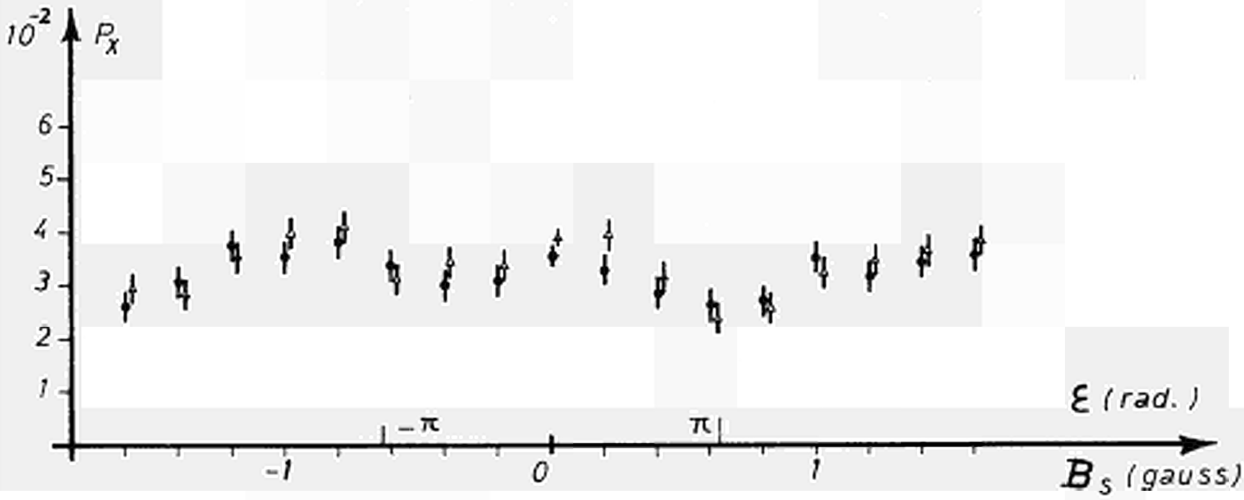

FIG. 2 - P_x modulation curves. Round points : stray field compensation. Triangular points : no compensation.

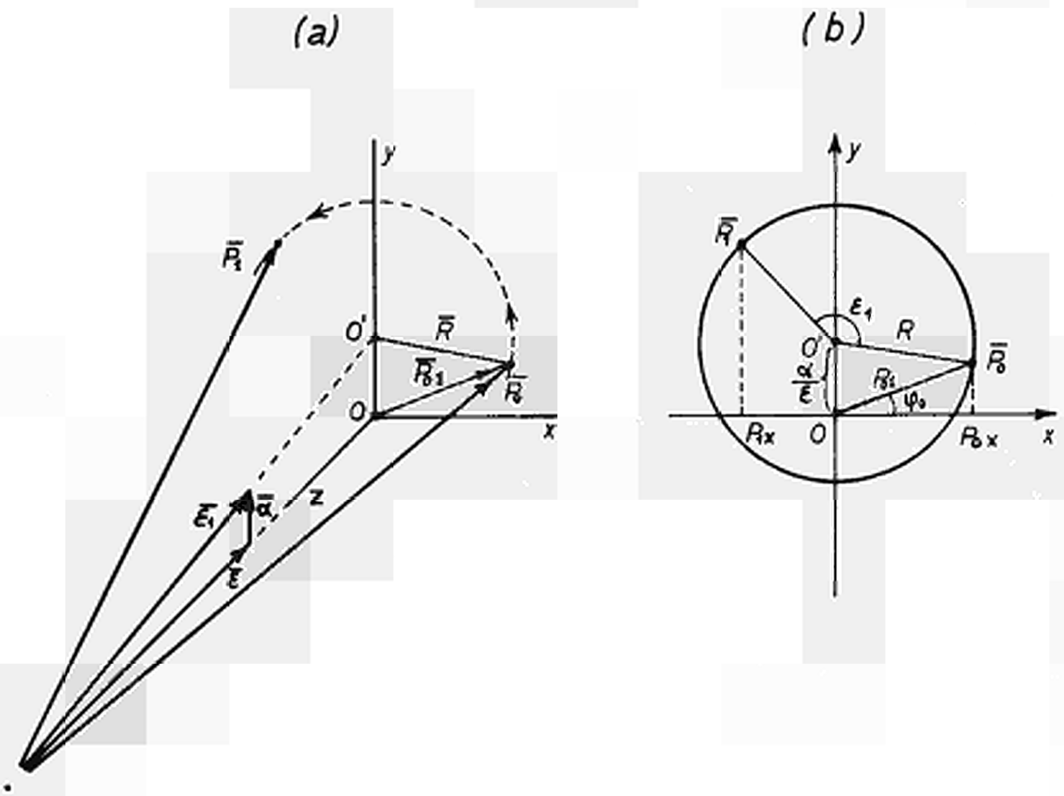

FIG. 3 - Analysis of the $\overline{P}$ modulation (see text).

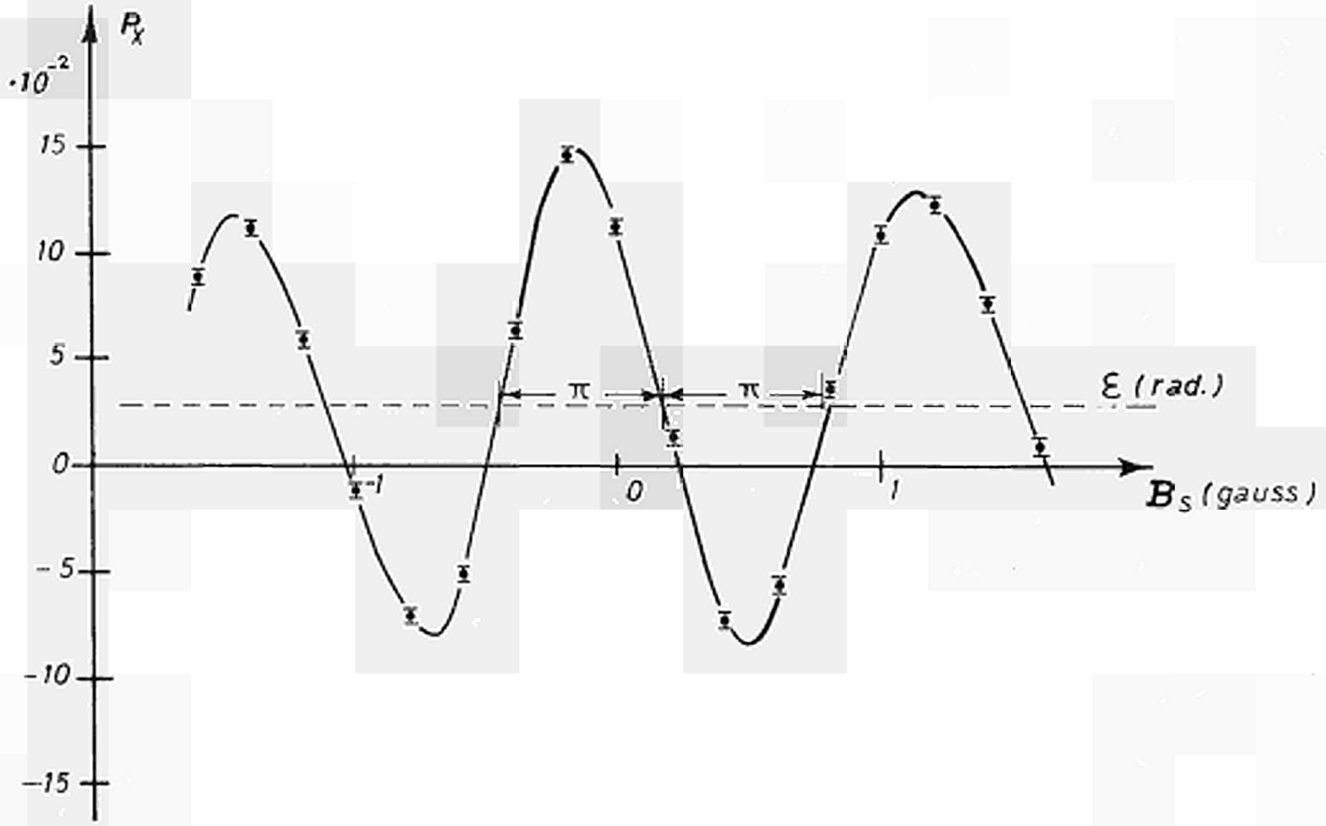

FIG. 4 - Enhanced sinusoidal modulation for the modulation period calibration

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Alfred Nobel

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