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NEUTRON SPIN PRECESSION IN POLARIZED NUCLEAR TARGETS

by

M. FORTE

1974

Joint Nuclear Research Centre
Ispra Establishment – Italy

Physics Division

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The neutron spin precession, modified by a spin dependence of the neutron wave attenuation, is analitically described.

The principles and preliminary results are presented of new experiments which mea- sure directly a neutron spin rotation, proportional to the spin dependent real part of the scattering amplitude.

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ABSTRACT

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KEYWORDS

NEUTRON BEAMS
NEUTRONS
SPIN
PRECESSION
POLARIZED TARGETS
NUCLEAR POTENTIAL
SCATTERING AMPLITUDES
ENERGY LOSSES
ANALYTICAL SOLUTION

1. INTRODUCTION

When a neutron is transmitted through a polarized nuclear target where the average of the spin dependent part of the nuclear potential is not vanishing, a precession of the neutron spin is produced and effects analogous to the ordinary magnetic precession become observable.
The nuclear precession of neutrons was aforeseen by Baryshevskii and Podgoretskii, [(1)], who have also proposed a sort of neutron resonance depolarization experiment, to detect the nuclear shift in the precession frequency of the neutron spin in a polarized target, placed in a magnetic field. With appropriate conditions, the neutron resonance can be stimulated by the nuclear interaction coupling the neutron spin with the nuclear spins precessing in the magnetic field.

Experiments on this line, recently performed by Abragam et al. [(2)], were successfull to demonstrate the nuclear precession of slow neutrons. In the future, a main object of these experiments will be the determination of the spin dependent part of the nuclear scattering amplitude.

As we had previously pointed out [(3)], a most sensitive method, to measure spin interactions of this type, is a direct measurement of the neutron spin rotation angle. Following this line we have undertaken neutron precession experiments [(4)], of which we will give a preliminary account. We will first discuss some theoretical aspects of the neutron precession in connection with the neutron scattering, which may be interesting also for the interpretation of neutron precession experiments.

In particular, we will give a complete description of the evolution of the neutron spin in a polarized nuclear target.

2. OPTICAL POTENTIAL AND NUCLEAR PRECESSION OF NEUTRONS

a) We consider the transmission of a neutron beam in a large uniform medium.

The transmitted coherent wave is formed by the coherent superposition of the incoming wave and of the wavelets scattered at the target centres, leaving the target in the initial state.
A coherent wave satisfies a one particle equation with a suitable complex momentum-dependent potential (optical potential). In a large uniform medium, the solution is a superposition of plane waves. The wave number k', for a given external wave number k, is determined by the real part of the optical potential, by the relation valid for weak potentials ($|V| < E$)

$$k'^2 \approx k^2 - 2m\hbar^{-2}\,\mathrm{Re}V_{k'} \quad , \tag{1}$$

which defines also the refraction index $n = k'/k$. The imaginary part of the optical potential simply introduces a wave attenuation. In what follows we will be concerned with the real part of the optical potential in connection with the neutron interaction with the target centres. On the other hand we will assume that the attenuation of the transmitted wave, due to nuclear absorption as well as to any kind of scattering away from the propagation direction, can be determined from the experimental cross section data.
In a multiple scattering approach followed in (5), the first order approximation for V is, considering n scattering centres,

$$V_1 = \sum_{i=1}^{n} \langle t_i \rangle$$

where $\langle t_i \rangle$ is the coherent part of the transition operator for the two body scattering inside the target, that is the average of t_i over the initial state of the target, taking into account only neutron scattering with no energy or spin exchange with the target.

The higher order corrections to the optical potential arise from multiple scattering and vanish unless target excitations and deexcitations to the initial state occur by successive neutron scattering at different target centres.

However, in ordinary targets, where the interparticle correlation range is very short compared to the neutron scattering mean free path, the latter contribution needs not to be taken into account.

The operator t_i can usually be approximated by the free two particle operator $t_i^{(f)}$ (impulse approximation).
The validity of the impulse approximation will be discussed later.

Using the known relation between the transition amplitude and the scattering amplitude, one can derive the ordinary form :

$$V_{k'} = -2\pi \hbar^2 m^{-1} \quad N\langle f_{k'}(0)\rangle \tag{2}$$

for the optical potential in an extended medium, produced by a large number of identical atoms with uniform density N , where $\langle f_{k'}(0)\rangle$ is the free atom forward scattering amplitude, averaged over the initial target state.

We will consider now the spin dependent part of the optical potential, in a target including nuclear and, eventually, magnetic polarization.

We have :

$$\langle f(0)\rangle = \langle f_{nucl}(0)\rangle + \langle f_{mag}(0)\rangle$$

Considering only s - wave nuclear scattering, we have

$$f_{nucl} = \frac{I+1}{2I+1} f^+ + \frac{I}{2I+1} f^- + \frac{\vec{\sigma}\cdot\vec{I}}{2I+1}(f^+ - f^-)$$

being I the nuclear spin, $\frac{1}{2}\vec{\sigma}$ the neutron spin, and f^+, f^- the amplitudes for the scattering with $J = I + \frac{1}{2}$ and $J = I - \frac{1}{2}$, respectively.

Using the known expression for f_{mag} one obtains (taking into account also the applied magnetic field) the optical potential :

$$V = -2\pi \hbar^2 m^{-1} \; N \, f_{coh} + \frac{\bar{\sigma}\cdot\langle\bar{I}\rangle}{2I+1} \; (f^+ - f^-)] - \mu\bar{\sigma}\cdot\bar{B} \qquad (3)$$

for a density N of identical atoms.

The real spin dependent part of the optical potential is then :

$$\mathrm{Re}\; V_\sigma = - \bar{\sigma} \cdot (2\pi \hbar^2 m^{-1} \; N \, f_{prec} \; \bar{p} + \mu \bar{B}) = \bar{\sigma} \cdot A$$

where $\bar{p}$ represents the orientation and the degree of nuclear polarization, and

$$f_{precession} = \frac{I}{2I+1} \quad \mathrm{Re}\; (f^+ - f^-) \qquad (4)$$

is an amplitude defined for convenience.

The vector $\bar{A}$ can be assumed oriented along the $\hat{z}$ axis.

b) The form of the potential suggests that the neutron spin will precess around the $\hat{z}$ axis with a precession frequency $\omega = 2\hbar^{-1}A$. The frequency is independent on the neutron velocity, as far as f (0) does not vary with k'.

For a complete description of the evolution of the neutron spin in the target potential, more detailed considerations are needed, taking into account the spin dependent neutron attenuation in the polarized medium, which can result from nuclear and magnetic scattering and from nuclear absorption. Part of the following results have been derived in [1].

A coherent plane wave propagating in a direction $\hat{r}$, can be expanded into the solutions of the wave equation with $\sigma_z = \pm 1$:

$$\psi = \psi\,(r) = a_1 \; \exp(ik_1' r).\exp(-\tau_1 r) \; \begin{vmatrix}1\\0\end{vmatrix} \; +$$

$$+ \; a_2 \; \exp(ik_2' r) \; .\exp(-\tau_2 r) \; \begin{vmatrix}0\\1\end{vmatrix} \; .$$

For the two spin components, we have assumed different wave numbers, according to (1) and (3), and different attenuation coefficients τ_1 and τ_2, the difference $(\tau_1 - \tau_2) = \Delta\tau$ corresponding to the transmission polarization cross section.

Since we look at a phenomenon due to a coherent phase change, we need not to distinguish between a single neutron and a fully polarized neutron beam. Taking $a_1 = a_2$, we assume, at r = 0 an initial state completely polarized in the x direction.

At a depth r in the medium, we obtain :

i) Intensity attenuation :

$$(\psi^*\psi)/(\psi^*(0)\psi(0)) = \frac{1}{2}\ [\exp(-2\tau_1 r) + \exp(-2\tau_2\ r)]$$

ii) Relative phase shift of the two spin components :

$$(k_1' - k_2') \cdot r = \Delta k' \cdot r = \varphi ,$$

that is the precession angle of the spin around the z axis.

iii) Polarization components (averaging in the spin space only):

$$P_x = \langle\psi|\sigma_k|\psi\rangle / (\psi^*\psi) = \cos(\Delta k' r) / \cosh(\Delta\tau \cdot r) = \cos\varphi/\cosh(\frac{\Delta\tau}{\Delta k'} \cdot \psi)$$

$$P_y = \langle\psi|\sigma_y|\psi\rangle / ((\psi^*\psi) = \sin\varphi/\cosh\ (\frac{\Delta\tau}{\Delta k'} \cdot \varphi)$$

$$P_z = \langle\psi\ \sigma_z\ \psi\rangle/(\psi^*\psi) = \tanh\ (\frac{\Delta\tau}{\Delta k'} \cdot \varphi)\quad (*)$$

We verify that $P = (P_x^2 + P_y^2 + P_z^2)^{\frac{1}{2}} = 1$

The polarization component in the (x,y) plane is

$$(P_x^2 + P_y^2)^{\frac{1}{2}} = P_\perp = 1/\cosh\ (\frac{\Delta\tau}{\Delta k'} \cdot \varphi)$$

(*) Note that, in the present case, P_z takes the same value which one would obtain by transmitting a beam completely unpolarized at r = 0 (incoherent mixture of $\sigma_z = \pm 1$ states with equal weights)

Let us consider an indefinitely extended medium and represent $\overline{P} = (P-0)$, taking as a parameter $\varphi = \Delta k' . r$ in the range $(-\infty, +\infty)$, (see Fig. 1).

The point P describes a spiral lying on the unit sphere, with polar axis z, with uniform angular increment $(d\varphi/dr) = \Delta k'$, asymptotically terminating at the two poles. We have arbitrarily assumed an evolution toward $P_z = +1$, with increasing r. By convention, we have taken $\overline{P}(r = 0) = +\hat{x}$, however the spiral can be used, by an obvious procedure, to determine the polarization change $\bar{P}(r_2) - \bar{P}(r_1)$ in a target thickness $(r_2 - r_1)$, for any given initial polarization $\bar{P}(r_1)$. The exact conditions $\bar{P}(-\infty) = -z$ and $\bar{P}(+\infty) = +z$ correspond to the two stationary spin states $\sigma_z = +1$ admitted by the wave equation.

The importance of the spiral effect in the experiments can be estimated from the relation : $(d\vartheta / d\varphi) = (P_{\perp} . \Delta\tau)/(\Delta k')$ where ϑ is the azimuth angle of P.
For slow neutrons is, ordinarily, $(\Delta\tau / \Delta k') << 1$ and, therefore, a negligible spiral effect is expected in experiments of the type considered later on, in which small φ rotations are measured.

On the other hand, in neutron resonance depolarization experiments, a large number of neutron spin revolutions are produced by the target polarization and the influence of the spiral effect might be considerable, in certain cases.

c) We conclude this treatment with a simplified discussion of the conditions for the validity of the impulse approximation, which has been assumed at the beginning. The impulse approximation applies when the target atoms can be considered weakly bound in comparison with the neutron energy, or, less restrictively, when the binding potential remains nearly constant for the recoiling atom, during the scattering interaction with the incident neutron. The correction to the impulse approximation is estimated of the order [6] :

$$\Delta \approx \left| \frac{f}{\lambda} \frac{U_{av}}{2M R^2} t_c^2 \right|$$

where M is the atom mass, U_{av} (≈ 1 eV) is the average binding potential, R ($\approx 10^{-8}$ cm) is the potential range, and t_c is the time duration of the collision.

Taking, for non resonant scattering, $t_c = \hbar/E$, we have

$$\Delta \gtrsim 5\cdot 10^{6}(|f|/M_{amu})\cdot E^{-3/2}$$

So, the impulse approximation is accurate also at neutron energies well below the atom binding energies for ordinary values of f ($<10^{-11}$ cm). The case of neutron resonance scattering has to be considered separately.
At a neutron resonance, we can take, for simplicity, $(f^{+} - f^{-}) = \pm f_{res}$, with f_{res} represented by a single level resonance formula. (*)
According to (4), we have :

$$f_{prec} \approx \pm \frac{I}{2I+1} \frac{\lambda_o(E-E_o)(\Gamma_n/2)}{(E-E_o)^2+(\Gamma/2)^2} \cdot$$

The precession amplitude has a sharp oscillation, changing the sign at $E = E_o$. The collision time, at resonance, is $t_c = \hbar/E + Q$, including a "time delay" $Q \approx \hbar(\Gamma/2)^{-1}$ corresponding to the lifetime of the scattering state.
Assuming $\Gamma << E_o$, and being, near the resonance,

$$|f| \lesssim \lambda_o \Gamma_n/\Gamma$$

we have, as a rough estimate,

$$\Delta \lesssim 10^{-2} (\Gamma_n/\Gamma)/(M_{amu} \Gamma_{ev}^2)$$

So, in the case of resonant scattering, the impulse approximation seems to be fairly accurate, at least when the scattering nuclei are sufficiently heavy, and with the favourable concurrence of large absorption widths.

The previous considerations ensure, within the limits which we have discussed, that the neutron nuclear precession measurements are uniquely related to the nuclear scattering amplitudes, while the target structure and dynamical properties can be ignored, at this stage of the research.

(*) The sign + or - depends on whether f^{+} or f^{-} is resonant

3. EXPERIMENTS :

Various aspects and possibilities of neutron nuclear precession experiments are discussed more estensively in [4].

A comparison of the spin rotation effect with a measurement of the polarization transmission (or scattering) cross section is obtained, for a weakly polarized target, from the relation

$$\varphi/(\Sigma_{pol}\cdot r) = \Delta k/\Delta_{\tau} \approx ƛ / |f_o| \qquad (4)$$

where f_o is the unpolarized scattering amplitude. Accordingly, large gains in the sensitivity are expected with the new spin rotation experiments, typically four orders of magnitude with thermal neutrons.

No substantial gain is expected at a neutron resonance, even at low energy, being $|f_o| \approx |f_{res}| \approx ƛ$.

A preliminary experimental set-up is schematically represented in Fig.2.

The polarization vector of the neutron beam, reflected from a magnetic mirror, is turned into the $\hat{x}$ direction, by the spin rotator (P_x).

The beam, suitably collimated, crosses a pair of identical superconducting coils A,B, having rectangular loops, which are fed by the same current. The fields, inside the coils are of the same intensity, but of opposite polarity, $\bar{H}_A = H\hat{z}$, $\bar{H}_B = -H\hat{z}$ so to produce equal and opposite rotations of $\bar{P}$ in the (x,y) plane, thus resetting $\bar{P}$ at the original direction.

In practice, however, a small deflection $\varphi = \varphi_o$ may result. By feeding a similar coil C, crossed by the beam, known rotations can be produced, both for adjustement and calibration purposes.

The angle φ is measured by a system (P_y = which analyses the component $P_y = P \sin\varphi$.

One of the measuring methods followed works with a pair of identical targets T_A, T_B, which are statically polarized in the fields of the paired coils, the polarization being $P_A = p$ and $p_B = - p$, respectively, along the z direction.

Each of the two targets is alternately positioned in the neutron beam (positions 1 and 2 in the figure), and the corresponding rotations are observed :

$$\varphi_1 = \varphi\ (p_A) + \varphi_o \quad \text{and} \quad \varphi_2 = \varphi\ (p_B) + \varphi_o\ ,$$

respectively.

The difference $(\varphi_1 - \varphi_2) = \varphi(p_A) - \varphi(p_B) = 2\ \varphi\ (p)$ measures, in addition to the neutron nuclear precession, the magnetic precession due to the induced target magnetization (B - H). The latter can be easily accounted for, using diamagnetic or weakly paramagnetic substances.

Fig. 3 shows the results obtained with protons, using a pair of polyethylene targets polarized in a field intensity $H \approx 600$ G, at the temperature of the liquid helium bath, of $\sim 4{,}2\ ^{o}$K, polarization degree $p \approx 1{,}46 \times 10^{-5}$. Two measurements of the nuclear precession effect $(\varphi_1 - \varphi_2) \approx (\varphi_1' - \varphi_2')$, obtained at two known field intensities in the calibration coil C, can be directly compared with the magnetic precession difference, which is measured by :

$$(\varphi_o - \varphi_o') = (\varphi_1 + \varphi_2)/2 - (\varphi_1' + \varphi_2')/2$$

This calibration method is independent of the neutron velocity spectrum and polarization degree. The measured precession amplitude reproduced the value calculated from the n-p scattering amplitudes, within the experimental uncertainties, of the order of $\pm$ 10%. The target diamagnetism contributed less than a percent correction. Much better accuracies are expected with this method, after a few improvements.

The sensitivity of the method is limited by the highest field intensity, in the paired coils, which is compatible with a regular and controllable neutron polarization.

This limit can be largely overcome when a target with a conveniently long nuclear spin relaxation time is available. The target is placed in a strong field (several kG), supplied by a superconducting coil, D in Fig. 2, and, after the polarization

build-up, is transferred into a coil of the pair, where it is measured.
Fig. 4 shows the nuclear precession effect, decaying simultaneously with the proton polarization, in a hexamethylbenzene target. The baseline corresponds to the static polarization in the weak field of the paired coils, $H \approx 160$ G.
Occasionally, the proton polarization degree, reached in the strong field during the allowed time was a modest fraction of the equilibrium value.
The evident advantage of this method is to enhance the measurable nuclear precession, by a large factor. On the other hand, the relative contribution of the induced target magnetization is minimized.

A detailed report on these experiments is the subject of a next paper [7].

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Figure captions

Fig. 1 Representation of the spiral described by the polarization vector $\bar{P} = (P-0)$, see eq. (5).

a'), a'') projections on the (x, y) plane of the loops lying on the hemispheres $z > 0$ and $z < 0$, respectively.

b) projection of the spiral on the (x, z) plane.

Chosen value of the coefficient $\Delta\tau/\Delta k' = 0,2/\pi \simeq 0.0636$.

Fig. 2 Scheme of the experimental set up.

P_x = neutron polarizer and spin rotator, P_y = analyzer of the component P_y. n = polarized neutron beam. A, B)= paired coils with fields in opposition. C = calibration coil. T_A, T_B = polarized nuclear targets. D = coil for target polarization in strong field. E = liquid helium cell. S = neutron beam collimators. M = beam monitor. N = analysed neutron counter.

Fig. 3 Neutron precession measured with a pair of polyethylene proton targets, T_A and T_B.

φ_1, φ_2 = rotations with T_A and T_B in the beam, respectively

φ'_1, φ'_2 = idem, with a field change in the calibration coil.

(The φ scale is approximate).

Fig. 4 Decay of the neutron precession effect, φ_d, in a hexamethylbenzene proton target. φ_b = baseline (weak static polarization). t_p = polarization build-up period.

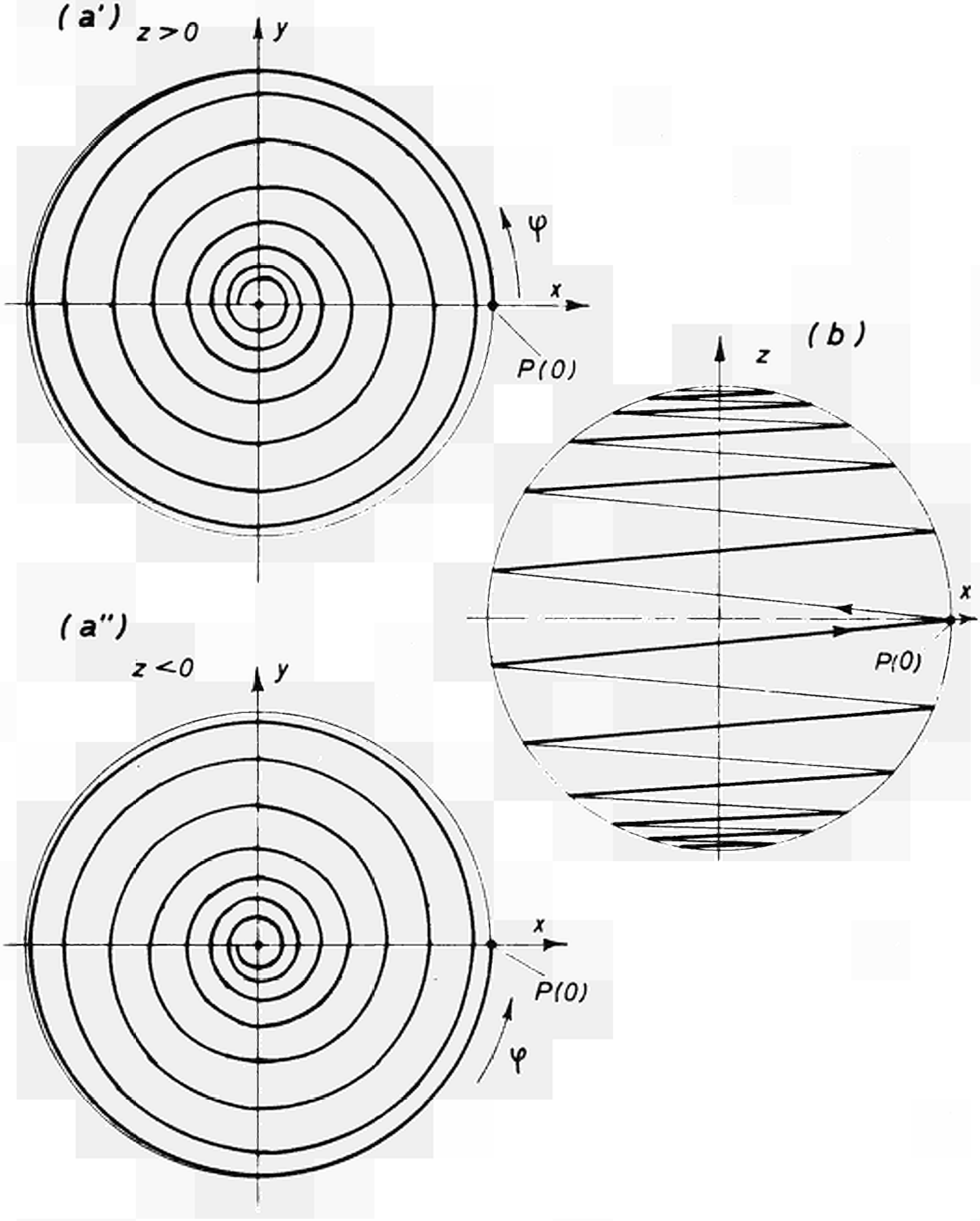

Fig. 1

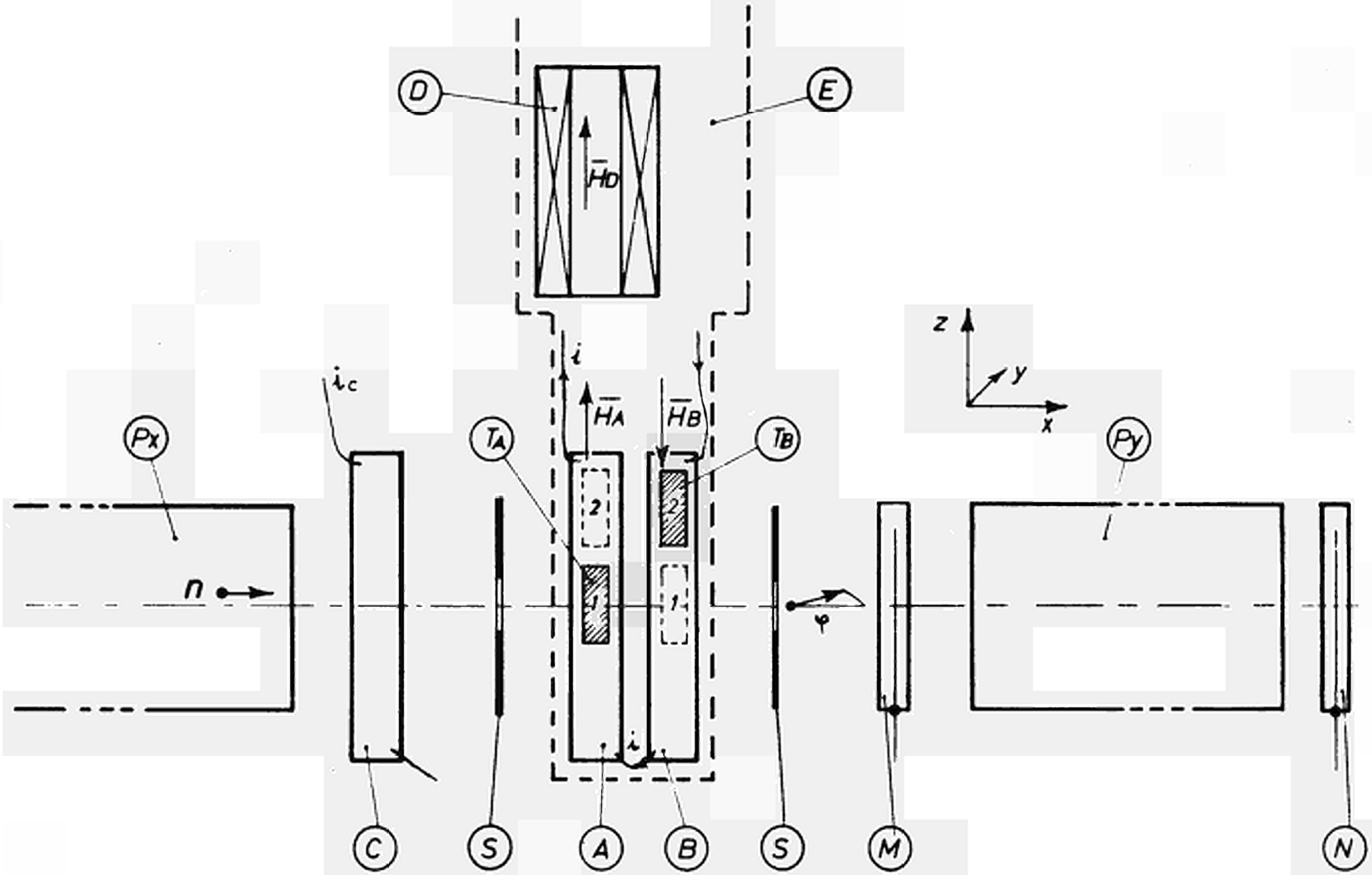

Fig. 2

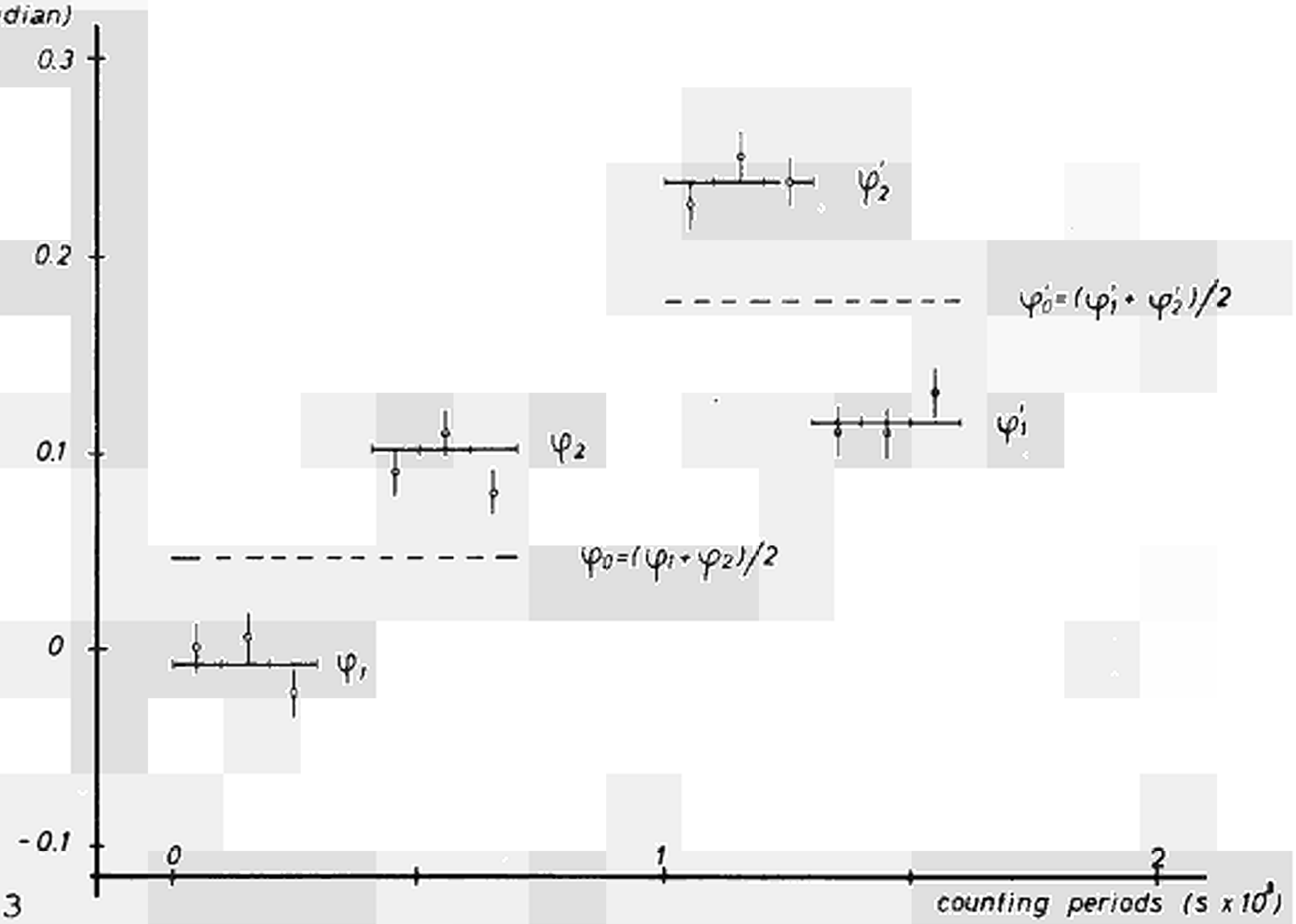
φ (radian)
0.3
0.2
0.1
0
- 0.1
0
1
2
counting periods (s x 10³)
φ'₂
φ'₀=(φ'₁ + φ'₂)/2
φ'₁
φ₂
φ₀=(φ₁ + φ₂)/2
φ₁

Fig.3

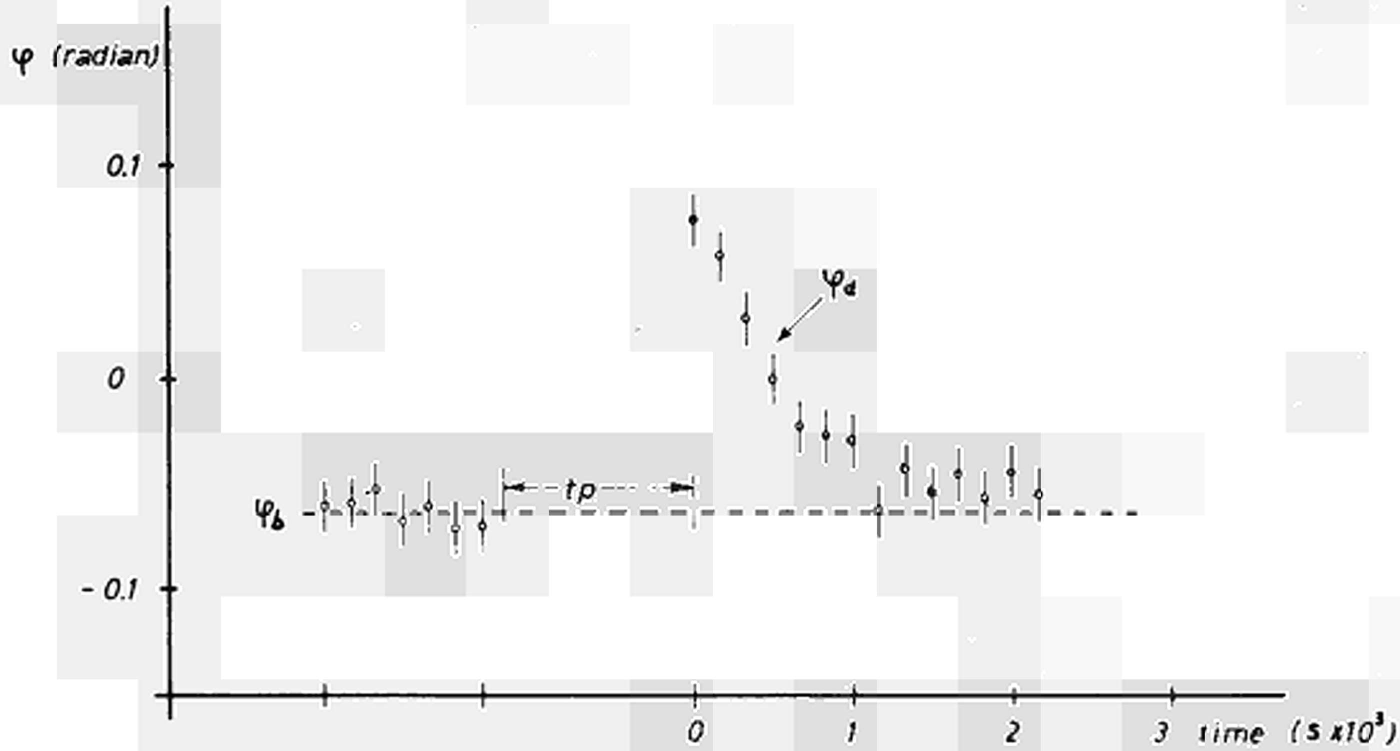
φ (radian)
0.1
0
- 0.1
φd
φb
tp
0
1
2
3
time (s x10³)

Fig 4

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