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Quantum Measurements in Time Dependent Neutron Interferometry (*)

by

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ABSTRACT. — The perfect crystal neutron interferometer has been used continuously for test measurements on quantum mechanics. Polarized neutrons were used to perform the quantum mechanical spin-superposition experiment on a macroscopic scale. This experiment was continued with two resonance coils in the beams, in which the coherence persisted, even if an energy exchange occurred with certainty between the neutron and the resonator system. A quantum beat effect was observed when slightly different resonance frequencies were applied to both beams. In this case, an extremely high energy sensitivity of 2.7×10^{-19} eV was achieved. Neutron spectroscopy is thus able to cover time domains from microscopic to macroscopic scales. All the results obtained until now are in agreement with the formalism of quantum mechanics and stimulate discussion about the interpretation of this basic theory.

RÉSUMÉ. — L'interféromètre à neutrons à cristal parfait a servi sans discontinuer à faire des mesures tests en mécanique quantique. Des neutrons polarisés ont été utilisés pour effectuer une expérience de superposition de spins quantique à l'échelle macroscopique. Cette expérience fut reprise, en interposant deux solinoïdes résonnants dans les faisceaux et la cohérence montrée persister même si un échange d'énergie s'effectuait de manière certaine entre le neutron et le système résonnant. Un effet de battement quantique a été observé quand des fréquences de résonance légèrement différentes sont appliquées aux deux faisceaux. Dans ce cas une sensibilité en énergie extrêmement grande ($2,7 \times 10^{-19}$ *ct*) a été

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atteinte. La spectroscopie de neutrons peut donc couvrir des domaines temporels allant de l'échelle microscopique à l'échelle macroscopique. Tous les résultats obtenus jusqu'à présent sont en accord avec le formalisme de la mécanique quantique et suscite des discussions sur l'interprétation de cette théorie fondamentale.

§ 1. INTRODUCTION

The perfect crystal interferometer represents a macroscopic quantum device with characteristic dimensions of several centimeters. The basis for this kind of X-ray or neutron interferometry is provided by the undisturbed arrangement of atoms in a monolithic perfect silicon crystal [*1*], [*2*]. An incident beam is split coherently at the first crystal plate, reflected at the middle plate and coherently superposed at the third plate (fig. 1). It follows immediately from general symmetry considerations that the wave functions in both beam paths, which compose the beam in the forward direction behind the interferometer, are equal ($\psi_0^{\mathrm{II}} = \psi_0^{\mathrm{II}}$), because they are transmitted-reflected-reflected (TRR) and reflected-reflected-transmitted (RRT), respectively. The system is based on Bragg diffraction from perfect crystals; therefore, the de Broglie wavelength of the neutrons is about 1.8 Å and their energy about 0.025 eV.

The whole theoretical treatment of the diffraction process is based on the dynamical diffraction theory, which can also be found in the literature for the neutron case [*3-8*].

A phase shift between the two coherent beams can be produced by nuclear, magnetic or gravitational interactions. In the first case, the phase shift is most easily calculated using the index of refraction n [*9*], [*10*].

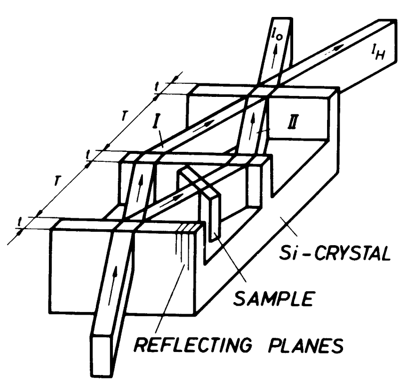

FIG. 1. — Sketch of the standard symmetric perfect crystal interferometer.

As in ordinary light optics the change of the wave function is obtained as follows:

$$\psi \to \psi_0 e^{i(n-1)kD} = \psi_0 e^{-iNb_c\lambda D} = \psi_0 e^{i\chi}. \tag{1.1}$$

Therefore, the intensity behind the interferometer is given by

$$I_0 \propto | \psi_0^{I} + \psi_0^{II} |^2 \propto (1 + \cos \chi). \tag{1.2}$$

The intensity of the beam in the deviated direction follows from particle conservation:

$$I_0 + I_H = \text{const}. \tag{1.3}$$

Thus, the intensities behind the interferometer vary as a function of the thickness D of the phase shifter, the particle density N or the neutron wavelength λ.

The magnetic interaction is caused by the dipole coupling of the magnetic moment of the neutron μ to a magnetic field B ($H = -\mu \cdot B$). Therefore, the propagation of the wave function is given by

$$\psi \to \psi_0 e^{-i(Ht/\hbar)} = \psi_0 e^{-i(\mu \cdot Bt/\hbar)} = \psi_0 e^{-i\sigma \cdot \alpha/2} = \psi(\alpha), \tag{1.4}$$

where α represents a formal description of the Larmor rotation angle around the field B $\left(\alpha = (2\mu/\hbar)\int B dt = (2\mu/\hbar v)\int B ds\right)$. This wave function shows the typical 4π-symmetry of a spinor

$$\psi(2\pi) = -\psi(0),$$
$$\psi(4\pi) = \psi(0), \tag{1.5}$$

whereas 2π-symmetry exists only for the expectation value

$$| \psi(2\pi) |^2 = | \psi(0) |^2. \tag{1.6}$$

The 4π-periodicity becomes visible in interferometer experiments, as predicted theoretically [*11-13*], and has been verified experimentally in early neutron interferometric experiments [*14*], [*15*], where the intensity for unpolarized incident neutrons was found to be

$$I_0 \propto | \psi(0) + \psi(\alpha) |^2 \propto \left(1 + \cos \frac{\alpha}{2}\right). \tag{1.7}$$

These results are widely debated in the literature. It should be mentioned that this 4π-symmetry can always be attributed to real rotations in the case of fermions [*16*], [*17*]. Today, the most precise value for the periodicity factor is $\alpha_0 = 715.87 \pm 3.8$ degrees [*18*]. This value provides only a small margin for speculation about SU(2)-symmetry breaking, but a new and more precise determination of α_0 is recommended. The 4π-periodicity effect has been observed for unpolarized as well as polarized neutrons, which demonstrates the intrinsic feature of this phenomenon and the self-interference properties involved in these kinds of experiments.

Under reasonable experimental parameters, the action of the gravitational field on the neutron is comparable to the nuclear and magnetic interaction. On the surface of the earth the pure gravitational term and the Coriolis term due to the earth's rotation have to be considered as

$$\mathrm{H} = mg \cdot r - \omega \cdot \mathrm{L}, \tag{1.8}$$

where g is the gravitational acceleration, r the space vetor from the centre of the earth, ω the earth's angular rotation velocity and $\mathrm{L} = r \times \hbar k$ the angular momentum of the neutron relative to the centre of the earth. This gravitational interaction causes the following phase shifts [*19-21*]

$$\mathrm{B}_g = -\frac{m^2 g \lambda \mathrm{A} \sin\theta}{2\pi\hbar^2}, \tag{1.9}$$

$$\beta_s = \frac{2m\omega \mathrm{A} \sin\theta_\mathrm{L} \sin\varepsilon}{\hbar}, \tag{1.10}$$

resulting in the following intensity modulation

$$\mathrm{I} \propto 1 + \cos(\beta_g + \beta_s). \tag{1.11}$$

A is the area enclosed by the coherent beams, θ is the angle of deviation of this plane from the horizontal, θ_L is the colatitude angle of the place, where the experiment is performed, and ε is the rotation angle around the vertical direction. Experiments performed by a US-group [*19*], [*22*], [*23*] have shown complete agreement between experiment and theory. Recently, the Dortmund interferometer group has extended these kinds of experiments to observe interferences in noninertial frames [*24*].

All the results of interferometric measurements obtained until now can be explained well in terms of the wave picture of quantum mechanics and the complementarity principle of standard quantum mechanics. Nevertheless, one should bear in mind that the neutron also carries well-defined particle properties, which have to be transferred through the interferometer. These are: its mass of $m = 1.6749543(86) \times 10^{-27}$ kg, its spin $\hbar/2$ and associated magnetic moment $\mu = -1.91304308(54)\mu_\mathrm{K}$, its effective radius of about 0.7 fm, and internal structure consisting of one « up » and two « down » quarks. Therefore, neutrons seem to be a proper tool for testing quantum mechanics of massive particles, where the wave-particle dualism becomes obvious.

All neutron interferometric experiments pertain to the case of self-interference, where during a certain time interval, only one neutron is inside the interferometer, if at all. Usually, at this time, the next neutron has not yet been born and is still contained in a uranium nucleus of the reactor fuel. Although there is no interaction between different neutrons, they have a certain common history within predetermined limits which are defined, e. g., by the neutron moderation process, by their movement along the neutron guide tubes, by the monochromator crystal and by the special interferometer set-up. Therefore, any real interferometer pattern contains single particle and ensemble properties together.

In this article, recent results obtained by our group during the period 1984-1987 will be presented [*25*], but no epistemological interpretation will be given. In this respect, the reader should refer to his own picture or to the related literature.

§ 2. SPIN STATE INTERFEROMETRY

We already reported on the experimental verification of the quantum mechanical spin superposition law on a macroscopic scale by means of neutron interferometry [*25*], [*27*], [*28*]. The principles of these experiments and the most important results are summarized in fig. 2. More experimental details can be found in the references mentioned above. There is a marked difference between the action of a static flipper and a resonance flipper, which has to be discussed in more detail.

In the first case (static flipper the wave function is changed by the flipper according to eq. (1.4), which has to be applied for polarized incident neutrons:

$$\begin{aligned} \psi \rightarrow e^{i\chi} e^{-i\sigma\alpha/2} \,|\, z \rangle &= e^{i\chi} e^{-i\sigma_y\pi/2} \,|\, z \rangle \\ &= -\, i\sigma_y e^{i\chi} \,|\, z \rangle = e^{i\chi} \,|\, -z \rangle . \end{aligned} \tag{2.1}$$

The rotation of the polarization vector around the y-axis has been postulated to be π [*29*]. Thus, two wave functions with opposite spin directions are superposed at the third plate as

$$\psi \propto (|\, z \rangle + e^{i\chi} \,|\, -z \rangle), \tag{2.2}$$

which corresponds to the situation proposed by Wigner [*30*] in 1963 to verify the quantum mechanical spin superposition law. In this case the intensities in the O- and H-beams are equal and the beams are polarized in the (x, y) plane, i. e., perpendicular to both the initial spin directions. The angle of the polarization in the (x, y)-plane is given by the nuclear phase shift:

$$P_0 = \frac{\langle \psi \,|\, \sigma \,|\, \psi \rangle}{I_0} = \begin{pmatrix} \cos \chi \\ \sin \chi \\ 0 \end{pmatrix} . \tag{2.3}$$

Thus, a pure initial state is transferred to a pure final state. The interference pattern appears only if a polarization analysis is performed in the $|\, x \rangle$-

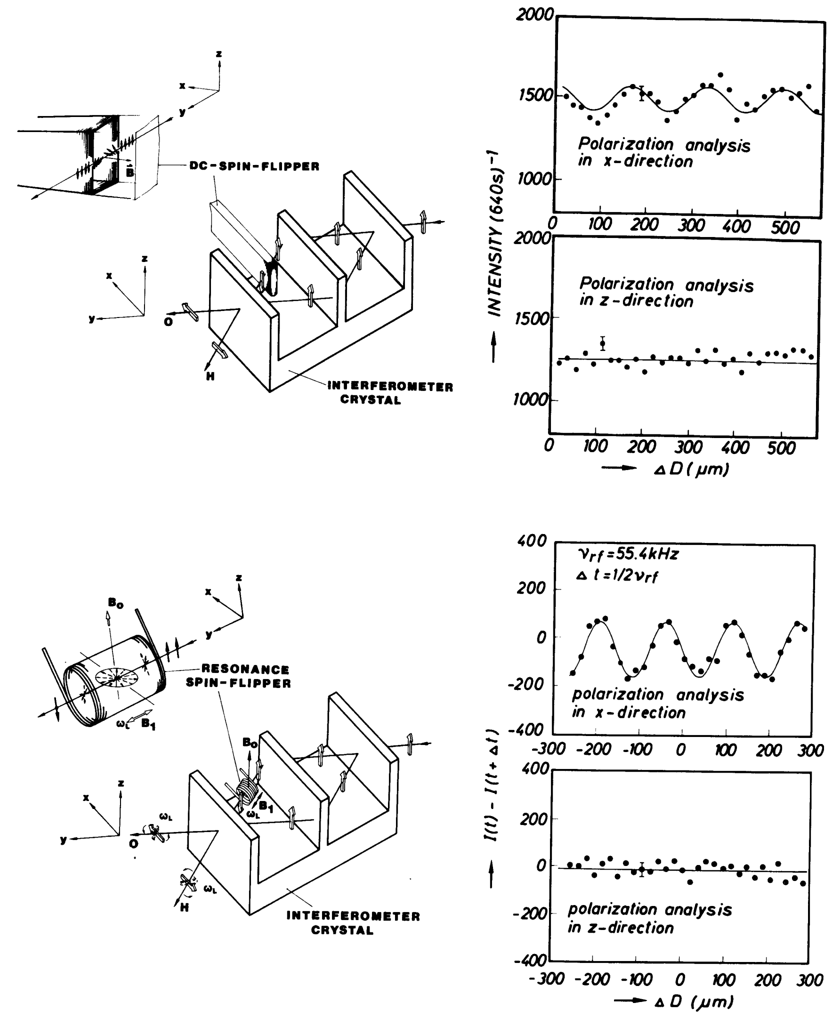

FIG. 2. — Sketch of the static (above)
and the time-dependent (below) spin superposition experiment with characteristic results.

or the $|y\rangle$-direction. If the analyzer is set in the $|z\rangle$- (or $|-z\rangle$-) direction, no intensity modulation is observed. The intensity is in this case exactly the same as when the $|-z\rangle$- (or $|z\rangle$-) beam through the interferometer was blocked. Nevertheless, the question whether the neutrons transmitted through a $|z\rangle$-setting of the analyzer originate from the $|z\rangle$-beam inside the interferometer, remains an epistemological question not answered by the formalism of quantum mechanics. If this were not the case new possibilities for delayed-choice experiments would open up, where a decision about beam path or interference detection could be made after the beam has passed the interferometer device.

The second version of the spin superposition experiment was performed with a Rabi-type resonance flipper which is also commonly used in polarized neutron physics. This kind of interaction is time-dependent and, in addition to the spin-inversion, an exchange of the resonance energy $E_{HF} = \hbar\omega_r$ occurs between the neutron and the resonator system, which has to be considered in the interferometric experiment. This energy exchange was observed in a separate experiment, where the energy resolution ΔE of the apparatus was better than the Zeeman energy splitting ($\Delta E < E_{HF}$) [31]. For a complete spin reversal the frequency of the field has to match the resonance condition and the amplitude B_1 has to fulfill the relation $|\mu| B_1 l/\hbar v = \pi$, where l is the length of the coil. Oscillating fields are used instead of purely rotational fields and, therefore, only one component contributes to the resonance which causes a slight shift in the resonance frequency from the Larmor frequency $\omega_L = 2|\mu|B_0/\hbar$ due to the Bloch-Siegert effect $(\omega_r = \omega_L[1 + (B_1^2/16B_0^2)])$ [32], [33]. Thus, the wave function of the beam with the flipper changes according to

$$\psi \rightarrow e^{i\chi} e^{i(\omega-\omega_r)t} \,|-z\rangle . \tag{2.4}$$

Therefore, a spin-up and a spin-down state are superposed at the position of the third plate. The final polarization of the beam in the forward direction is given by

$$\mathbf{P} = \begin{pmatrix} \cos(\chi + \omega_r t) \\ \sin(\chi + \omega_r t) \\ 0 \end{pmatrix}, \tag{2.5}$$

and lies again in the (x, y)-plane but now rotates within this plane with the resonance (Larmor) frequency without being driven by a magnetic field. Therefore, a stroboscopic method was needed for the observation of this effect. The direction of the polarization in the (x, y)-plane depends on the status (phase) of the resonance field and has to be measured synchronously with this phase.

The observed interference pattern (fig. 2) demonstrates that coherence persists, although a well defined energy exchange between the neutron and the apparatus exists. Thus, an energy exchange is not automatically a measuring process. As we will see later on, the exchanged photon cannot be used for a quantum nondemolition measurement [34]. In our experiment, the following argument based on different uncertainty relations can be used: First, one single absorbed or emitted photon of the resonator cannot be detected because of the photon number-phase uncertainty relation, which can be written in the form [35], [36]

$$(\Delta N)^2 \times \frac{(\Delta S)^2 + (\Delta C)^2}{\langle S \rangle^2 + \langle C \rangle^2} \geqslant 1/4 , \tag{2.6}$$

where S and C can be expressed by the creation and annihilation operators, $C = (a_- + a_+)/2$ and $S = (a_- - a_+)/2i$, whose matrix elements couple coherent Glauber states. For our purpose this relation can be used in its simpler form

$$\langle \Delta N \rangle^2 \langle \Delta\theta \rangle^2 \geqslant 1/4 . \tag{2.7}$$

The uncertainty of the photon number of the resonator is minimized for a coherent state resonator by $\Delta N \simeq \sqrt{\langle N \rangle}$ [37] and, therefore, the lower limit for the phase uncertainty becomes $\Delta\theta \simeq a/2\sqrt{\langle N \rangle}$. Because in this kind of spin-superposition experiment the phase determination of the flipper field is required to be better than $\theta \leqslant 1/2$ for the stroboscopic method, it is impossible to observe a single absorbed or emitted photon ($\Delta N \geqslant 1$).The argument has to be changed if squeezed states of the electromagnetic field are considered, where $\Delta\theta$ can approach a limit of $\Delta\theta \simeq 1/2 \langle N \rangle$ [38], [39]. An explanation, which is not based on the number-phase uncertainty relation, can be found in the literature [34].

A second version of the beam path detection may be based on the observation of the energy change of the neutron. This can only be achieved, if the energy resolution of the instrument fulfills the relation $\Delta E \leqslant 2\mu B_0$. On the other hand, the stroboscopic measuring method requires time channels $\Delta t \leqslant 1/2\nu_{HF} = h/4 | \mu | B_0$, which provides another constraint on the experiment. Both conditions cannot be fulfilled with respect to the energy-time uncertainty relation concerning the beam parameters $\Delta E \Delta t \geqslant \hbar/2$. Therefore, we conclude that a simultaneous detection of the beam path through the interferometer and of the interference pattern remains impossible.

It has been argued by Vigier's group [40], [41] that new information about the particle-wave duality can be obtained with resonator coils in both coherent beams. They calculated the quantum potential and the beam trajectories [42], [43] within the frame of the causal stochastic view of quantum mechanics. Unfortunately the results of these calculations are identical with the results of ordinary quantum mechanics and, therefore, to discern between both points of view remains an epistemological problem. The corresponding experiments will be discussed in the next section.

§ 3. DOUBLE COIL EXPERIMENTS

The experimental arrangement for the double coil experiment is shown in fig. 3 [44], [45]. The final polarization lies in the $| -z \rangle$ direction and the energy transfer $\hbar\omega_r$ can be smaller or larger than the energy resolution ΔE because this information can not be in any way associated with a beam path detection. The lay-out for this experiment followed the proposal

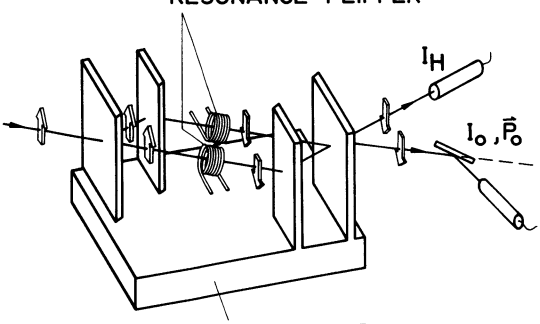

FIG. 3. — Sketch of the double resonance coil experiment.

of Vigier's group [*40*], [*41*]. According to our previous considerations the change in the wave functions with the resonance flippers tuned to the resonance frequency can be written for polarized incident neutrons ($| z \rangle$) and for different modes of operation as follows.

a) Both flippers are operated synchronously without a phase shift between the flipper fields:

$$\psi \rightarrow e^{i(\omega - \omega_r)t} | - z \rangle + e^{i\chi} e^{i(\omega - \omega_r)t} | - z \rangle . \qquad (3.1)$$

This results in an intensity modulation

$$I_0 \propto 1 + \cos \chi , \qquad (3.2)$$

which is independent of the flipper fields.

b) Both flippers are operated synchronously with a distinct phase relation Δ:

$$\psi_0 \rightarrow e^{-i(\omega - \omega_r)t} | - z \rangle + e^{i\chi} e^{i\Delta} e^{i(\omega - \omega_r)t} | - z \rangle . \qquad (3.3)$$

In this case, the intensity modulation is given by

$$I_0 \propto 1 + \cos (\chi + \Delta) . \qquad (3.4)$$

c) Both flippers are operated asynchronously with statistically fluctuating phase differences $\Delta(t)$ which average out during the measuring interval. Then

$$I_0 \propto \text{const} . \qquad (3.5)$$

It should be mentioned in this context that, even in this case, coherence phenomena can be observed if a stroboscopic investigation is performed ($I_0 = I_0(\Delta)$).

The results of these related experiments are shown in fig. 4. Complete agreement with the theoretical predictions is found. The interference properties are preserved, although an energy exchange $\hbar\omega_r$ certainly takes

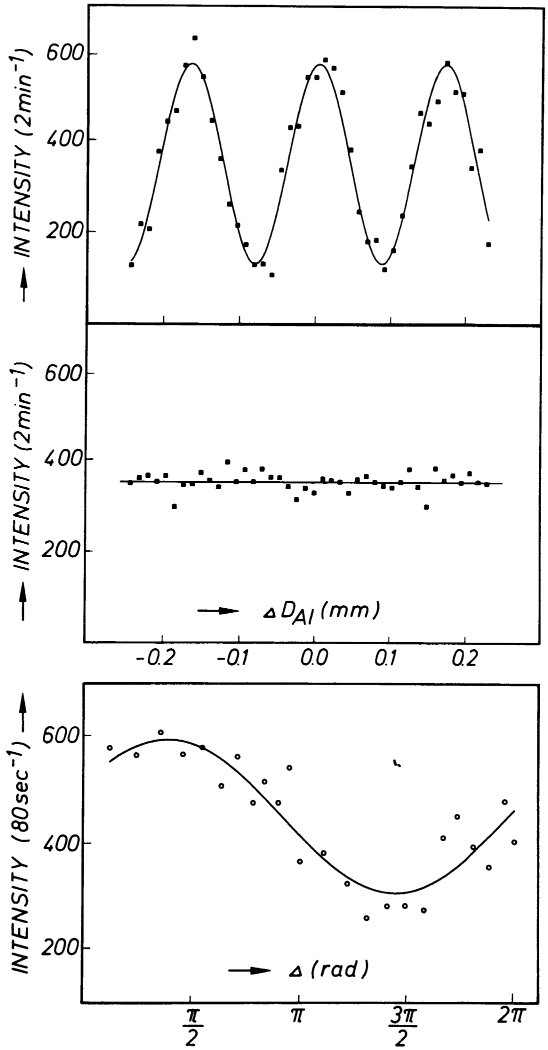

FIG. 4. — Results of the double coil experiments. Above: Synchronous flipper fields with $\nu_r = 71.90$ kHz (eq. (3.2)). Middle: Two slightly fluctuating independent flipper fields with $\nu_r = 71.92 \pm 0.02$ kHz (eq. (3.5)). Below: Interference pattern as a function of the phase shift Δ between both flipper fields at $\nu_r = 71.90$ kHz (eq. (3.4)).

place. Only quanta within a narrow energy band around $\hbar\omega_r$ and no others are excited inside the flipper resonator. Therefore, one could believe that the spin flip and the energy transfer process to the neutron occurred inside one of the two coils, which would demonstrate that the neutron has chosen one of the two possible paths. But even this rather weak statement would require the concept of pilot waves, quantum potentials, etc., leading immediately to questions about the interpretation of quantum mechanics, which are not the subject of this article. The situation with two slightly different resonance frequencies in both flipper coils will be discussed in the next section.

§ 4. MACROSCOPIC QUANTITIES IN UNCERTAINTY RELATIONS

By means of perfect crystal neutron optics the resolution in momentum or energy space can be increased to such an extent that the conjugate quantities reach macroscopic dimensions.

The experiments have been performed with monolithic multiplate systems by rotating a wedge shaped material around the beam axis; this privides a proper control ŏf small beam deflections in the horizontal plane, which is the only sensitive plane for perfect crystal reflections.

Although the wavelength of the neutrons is smaller than the width of the slit by a factor of about 10^8, the broadening of the central peak becomes visible due to the high angular resolution of such systems.

As an alternative to the high momentum resolution discussed before, an extremely high energy resolution can be achieved by a slight modification of the double coil experiment described in § 3. If the frequencies of the two coils are chosen to be slightly different, the energy transfer also becomes different ($\Delta E = \hbar(\omega_{r1} - \omega_{r2})$). The frequency difference can be made very small if high quality synthesizers are used for the field generation. The flipping efficiencies for both coils are always very close to 1 (better than 0.99). Now, the wave functions change according to

$$\psi \rightarrow e^{i(\omega-\omega_{r1})t} \,|\, -z \rangle + e^{i\chi} e^{i(\omega-\omega_{r2})t} \,|\, -z \rangle . \tag{4.1}$$

Therefore, the intensity behind the interferometer exhibits a typical quantum beat effect given by

$$I \propto 1 + \cos\,[\chi + (\omega_{r1} - \omega_{r2})t] . \tag{4.2}$$

Thus, the intensity behind the interferometer oscillates between the forward and deviated beam without any apparent change inside the interferometer [*44*], [*45*]. The time constant of this modulation can reach a macroscopic scale which is again correlated to an uncertainty relation $\Delta E \Delta t \geq \hbar/2$. Figure 5 shows the result of an experiment where the periodicity of the intensity modulation, $T = 2\pi/(\omega_{r1} - \omega_{r2})$, amounts to $T = (47.90 \pm 0.15)$s caused by a frequency difference of about 0.02 Hz. This corresponds to a mean difference of energy transfer ΔE between the two beams, $\Delta E = 8.6 \times 10^{-17}$ eV, and to an energy sensitivity of 2.7×10^{-19} eV,

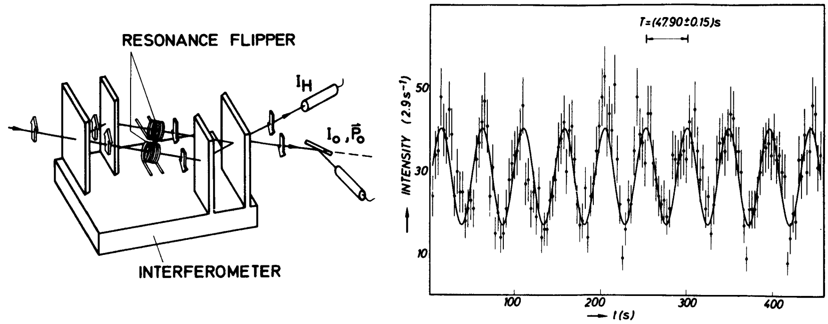

FIG. 5. — Quantum beat effect observed when the frequencies of the two flipper coils differ by about 0.02 Hz around 71 899.79 Hz.

which is better by many orders of magnitude than that of other advanced spectroscopic methods. This high resolution is strongly decoupled from the monochromaticity of the neutron beam, which was $\Delta E_B \simeq 5.5 \times 10^{-4}$ eV around the mean energy of the beam $E_B = 0.023$ eV in this case. It should be mentioned that the result can also be interpreted as being the effect of a slowly varying phase $\Delta(t)$ between the two flipper fields (see eq. (3.4)), but the more physical description is based on the argument of a different energy transfer. The extremely high resolution may be used for fundamental, nuclear and solid state physics applications.

An intrinsic lower limit for the energy width ΔE_i of the neutron beam is caused by its lifetime, $\tau = 925$s. According to $\Delta E_i \tau \geqslant \hbar/2$, $\Delta E_i \simeq 3.5 \times 10^{-24}$ eV. The decay appears in both beam paths and contributes an attenuation factor $\exp(-t/\tau) = \exp(-l/\tau v)$, which is similar to those discussed in § 2. It may be possible in a new experiment to observe the decay of the neutron inside the interferometer by measuring the decay products, which would make an assignment to a certain beam path possible.

§ 5. DISCUSSION

All the results of the neutron interferometric experiments are well described by the formalism of quantum mechanics. According to the complementarity principle of the Copenhagen interpretation, the wave picture has to be used to describe the observed phenomena. The question as to how the well-defined particle properties of the neutron are transferred through the interferometer, is not meaningful within this interpretation, but it should be an allowed one from the physical point of view. Therefore, other interpretations should also be included in the discussion of such experiments. We have always tried to perform unbiased experiments and do not wish to interfere with any epistemological interpretation of quantum mechanics. Perhaps in the future new proposals for experiments will be formulated, which permit a unique decision between different interpretations. As an experimentalist, one appreciates the pioneering work of the founders of quantum mechanics, who created this basic theory with so little experimental evidence. Now although we have much more direct evidence, even on a macroscopic scale, one nevertheless notices that the interpretation of quantum mechanics goes beyond human intuition in certain cases. Only two aspects of the experiments discussed before should be repeated: how can each neutron in the spin-superposition experiment be transferred from an initial pure state in the $| z \rangle$-direction into a pure state in the $| x \rangle$-direction behind the interferometer, if no spin turn occurs in one beam and a complete spin reversal occurs in the other beam path? How can every neutron have information about which beam to join behind the interferometer, when a slightly different energy exchange occurs in both beams inside the interferometer and the time constant of the beat effect is by many orders of magnitude larger than the time of flight through the system?

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Note added: In the paper « Inelastic action of a gradient radio-frequency neutron spin flipper » by H. Weinfurter, G. Badurek, H. Rauch, D. Schwahn, to be published in *Z. Phys.*, **t. B 72,** 1988, p. 195, we present some results that show very clearly the energy transfer within a flipper coil.