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GENERALIZED AHARONOV-BOHM AND WHEELER-TYPE DELAYED CHOICE EXPERIMENTS WITH NEUTRONS

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Résumé. De nouvelles expériences dépendantes du temps à l'aide d'interférométrie à neutrons sont proposées. Elles permettraient de démontrer d'une part le rôle particulier que joue l'énergie potentielle dans la mécanique quantique et d'autre part la complémentarité dans les phénomènes d'interférence quantique.

Abstract. Novel time-dependent neutron interferometry experiments are proposed. These would elucidate the peculiar role of potential energy in quantum mechanics on the one hand and the complementarity in quantum interference on the other hand.

I - GENERALIZED AHARONOV-BOHM EFFECT

The magnetic Aharonov-Bohm (AB) effect /1/ has found several beautiful experimental verifications /2,3 and refs. therein/, thus demonstrating the particular significance of the vector potential in quantum mechanics /4/. In contrast, the verification of the electric AB-effect demonstrating the role of the scalar potential still faces considerable problems, because in such an experiment one would have to switch a voltage applied to a Faraday cage on and off while the electron is inside. With the small beam separation of present electron interferometers, arranging two separate Faraday cages on the two beam paths is a nontrivial problem. Also, due to the high electron speed GHz switching frequencies are required. With these frequencies, nonequilibrium currents may be non-negligible.

The concept of the electric AB-effect can easily be generalized if we realize, that the operationally significant feature of that effect is the demonstration of phase effects in an interferometer due to a time-dependent potential energy in the Schroedinger equation

$$(-\frac{\hbar^2}{2m}\nabla^2 + V(t)\psi) = i\hbar\frac{\partial}{\partial t}\psi, \qquad (1)$$

where V(t) is chosen such, that the only change of the wave function finally is the phase factor

$$\Delta\varphi = \frac{1}{\hbar}\int V(t)dt. \qquad (2)$$

with all other observables being unchanged. Thus, the only way to detect experimentally the presence of V(t) is interference with an unperturbed beam. This is quite different from a phase shift produced by a static potential. There, besides the phase shift a time retardation or advancement of the wave packet occurs. Such is not the case in an AB-type situation, because the phase shift (2) is non-dispersive. Recently, Aharonov /5/ has proposed "AB-experiments of the second kind", which he interprets as exchanges of modular momentum and modular energy.

The interaction of the neutron most easily accessible to time-dependent switching is the magnetic dipole interaction $V(t) = -\mu\vec{\sigma}.\vec{B}(t)$. Thus it is proposed here to apply a time-dependent magnetic field onto one beam path of an interferometer with the other beam path being screened from that field. In the simplest case, the time-dependent field would be switched on to a constant value after the neutron wave packet entered the magnet field region and it would be switched off again before it leaves that region. Therefore, in the ideal situation, the wave packet would neither be advanced nor retarded /6/. It is evident, that the magnetic field need not be of constant magnitude while it is on, which might be a helpful feature in the experimental realization of the effect.

An interesting point arises with respect to the polarization of the neutrons used. If the beams used are polarized, they have to be polarized such that they are in an eigenstate of the magnetic field. If such were not the case, we would have another observable, namely the polarization which would carry the information about the magnetic field. This arises, because the two different eigenstates would experience identical phase shifts, but with opposite sign which results in the Larmor precession angle α being just twice the phase shift of Eq. 2. Another possibility is the use of unpolarized neutrons, since Larmor precession there leaves the density matrix invariant and thus is undetectable.

One possible experimental verification can be done using the Laue-case double-crystal interferometer (Fig. 1) in a way similar to that of the spinor rotation /7/ or spin superposition /8/ experiments.

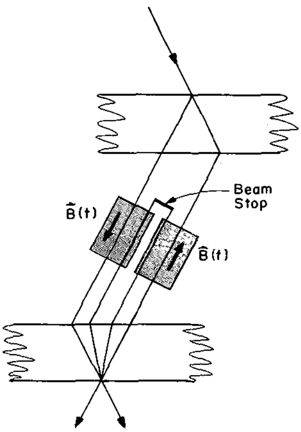

Fig. 1: Generalized Aharonov-Bohm experiment using time-dependent magnetic fields in a perfect crystal interferometer. The magnetic fields are to be switched on and off while the neutron is in the magnetic field region.

The magnetic fields necessary can easily be switched fast enough, which implies switching in the MHz frequency range. From the purist point of view a problem is, that in such an experiment the difference to static fields can hardly be shown. This is the property that such time-dependent fields do not lead to a decrease of interference contrast, while static ones do. The problem arises because a magnetic field that large that it shifts the wave packet (coherence length $\sim$ 50 - 200 wave lengths) far enough in the static case would be too strong ($\sim$ 10 kG) to be employable reasonably in these experiments.

Such would not be the case for an experiment with cold neutrons analogous to the double-slit interference experiment performed with $\sim$ 20 Å neutrons at the ILL /9/.

In that experiment, the coherence length was only about 6 wavelengths, which implies significantly smaller phase shifts for a destruction of interference contrast. Also, in such an experiment, the switching can be done significantly slower due to the lower neutron speed. The rather small beam separation of ∿ 100 μm makes the application of different magnetic fields on the beams rather difficult. This may be achievable using a current sheet (Fig. 2).

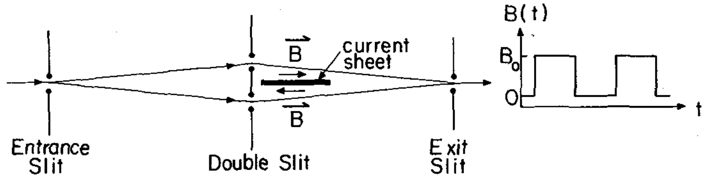

Fig. 2: Generalized Aharonov-Bohm experiment employing a current sheet in a double-slit interferometer for cold neutrons. The current is switched on and off such that a time structure for the magnetic field results as shown.

Longer wavelength neutrons (λ ≈ 100 Å) would imply larger beam separations and hence the application of a current sheet should be facilitated significantly.

II - DELAYED CHOICE EXPERIMENTS

It is commonly well known, that the interference pattern and the information about the path of a particle inside an interferometer are complementary quantities. For the double slit experiment it has been shown in the famous Bohr-Einstein dialogue /10/, that it is decided by the specific preparation of the experiment, i.e. the double slit or the entrance slit, which of the two complementary types of information are obtained. It had recently been argued by Wheeler /11/, that this decision can be delayed to times significantly after the passage of the neutron through the double slit. In particular, he proposes an experiment, where in a double-slit arrangement either a detector for the interference fringes or beam path detectors are swung in place at the last instant.

This experiment would be realizable using the double-slit interferometer for cold neutrons mentioned above (Fig. 3). It is proposed here to place behind the detector slit two detectors (e.g. scintillators) in close contact of each other. If now the detector slit is wide, the two beams can pass through it without significant diffraction and with properly aligned detectors, the firing of a given detector provides the information about the beam path followed by the neutron. But, in contrast, if the detector slit is narrow compared to the width of the interference fringes, the interference pattern can be obtained. Diffraction at that slit now prevents us from obtaining any information about the path the neutron took. For the parameters of the double-slit experiments already performed /9/ the two slit width correspond to about 100 μm and 20 μm, respectively. The delayed choice situation is then realized by switching from one slit width to the other while the neutron is in flight between double slit and observation screen. In the experiment mentioned the time available for that switching is as long as 25 ms. Again, λ ≈ 100 Å neutrons would imply longer flight times and larger interference pattern structures.

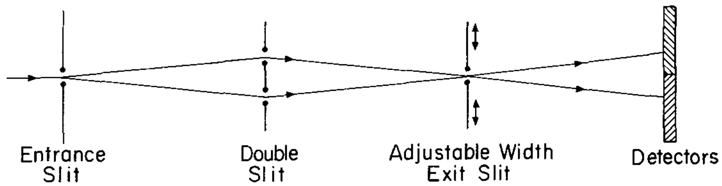

Fig. 3: Experimental setup for the demonstration of intermediate wave-particle behavior utilizing a cold-neutron double-slit interferometer with an exit slit of variable width. The delayed choice situation results of the slit width is switched after passage of the neutron through the double slit.

Another version of the delayed choice experiment with a double-slit setup utilizing polarized light has been proposed /12/. Such an experiment implies a very rapid switching of polarizers. Along the lines of the recent spin superposition experiment /8/ one could in principle perform an analogous experiment using a conventional three-crystal interferometer. In such an experiment the two oppositely polarized interferometer beams will be superimposed in the same way as in the spin superposition experiment. Measuring now the polarization component of the beam parallel to the z-axis would give information about the path taken inside the interferometer, while the interference phenomenon is reflected in the fact, that the superposition of +z and -z states points in a direction normal to the z-axis. It is clear, that this could easily be made into a delayed choice experiment by timing a spin-turn coil in front of the analyzer. This experiment is also a good example of the relation between the complementarity of the path information and the interference pattern on the one hand and the complementarity of other quantities, here the spin directions, on the other hand.

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