LONG WAVELENGTH NEUTRON INTERFEROMETRY

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Neutrons in the wavelength range around 20 Å have been used for various optical and interferometric experiments. Some of these experiments concerned precision measurements of the diffraction of neutrons at an absorbing edge and at single and double slit assemblies. The results are in perfect agreement with standard linear wave mechanics and place stringent limits on alternative nonlinear variants of the theory. Another experiment concerned the neutron Fizeau effect which demonstrates the relativistic transformation laws for Schrödinger wave functions. Future experiments with 80 - 100 Å wavelength neutrons will lead to an improvement over the precision of existing experiments. Also, neutron analogs to the Aharonov-Bohm effects and various time-dependent experiments will become realizable with a very long wavelength neutron interferometer using phase gratings as optical elements. Such gratings are based on the earlier successful tests of Fresnel lenses for very cold neutrons.

The successful development of perfect crystal neutron interferometers has led to various most elegant experiments /1,2/. The use of interferometers of this type implies Bragg diffraction and therefore is limited to neutrons in the thermal energy range. An extension to lower energies facilitates the use of time-switched devices and of large-area interferometers.

Concerning the terminology, we note, that cold neutrons are usually understood as those of a few Ångstrom wavelength, while ultracold neutrons are of energy low enough to be totally reflected at all angles of incidence. It is therefore useful, to denominate neutrons in between these two as very cold neutrons. This would then describe neutrons with temperatures between 10^{-2}K and 10K or wavelengths between ca. 10 Å and 300 Å /3/, obviously with some overlap. It is interesting to note, that presently only very little experimentation exists in that energy range. Yet, the advantages of that energy range for neutron optical and interferometric experiments are clear: the refractive index can already differ from unity enough to facilitate the operation of more conventional optical elements, and lenses etc. can still be penetrated by the neutrons. In the following I will firstly briefly review some of the experiments already performed with 20 Å neutrons and I will discuss some future possibilities.

The experiments performed hitherto utilized a beam from the cold source of the ILL High Flux Reactor monochromatized by quartz prism refraction /4/. With a wavelength of 20 Å detailed diffraction patterns at macroscopic objects may already be observed. For example, diffraction at a double slit assembly of 100 μm separation between the slits results in a 100 μm spatial separation between the peaks after a flight path of 5 m length. Interestingly, at that distance the width of the first Fresnel zone happens to be of the same magnitude.

Besides its demonstrational value, the study of diffraction at simple objects also serves as a tool for precision tests of standard quantum mechanics. For example, it has been conjectured by various authors, that the linear Schrödinger equation could be the limit of a higher nonlinear one /5/. In view of the epistemological relevance of the linearity, experimental tests are most useful despite the fact, that any possible nonlinear deviation has to be exceedingly small.

The most basic consequence of the linearity of quantum mechanics is the unrestricted validity of the superposition principle /6/. The most direct experimental test of linear quantum superposition is provided by the double-slit diffraction experiment /7/ (Figure 1). In particular, the experiment tests against any unknown non-unitary evolution of the two spatially separated states representing the two partial beams. Such a non-unitary evolution would result in a reduction of interference contrast as a function of evolution time. Parametrizing this reduction by an exponential law $\exp(-t/\tau)$ the excellent agreement between

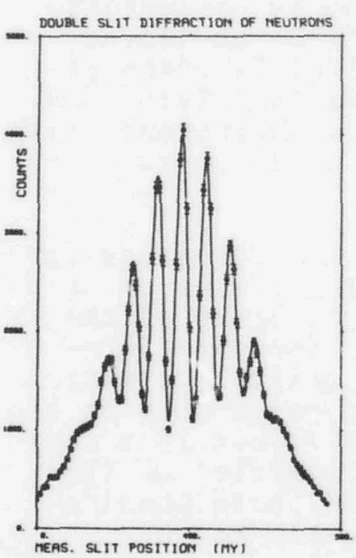

Figure 1: Diffraction of neutrons with a wavelength of 18.5 Å at a 22-104-23 μm absorbing double slit assembly. Experimental points shown with the prediction from standard linear quantum mechanics. The abscissa runs from 0 to 100 μm and the ordinate axis from 0 to 5000 counts.

linear quantum mechanical prediction and experiment (Fig.1) results in a lower limit of τ = 8sec. Future experiments with very cold neutrons will improve this limit by at least one order of magnitude.

Using the same experimental arrangement, diffraction at single slit assemblies was also studied. Figure 2 shows a typical

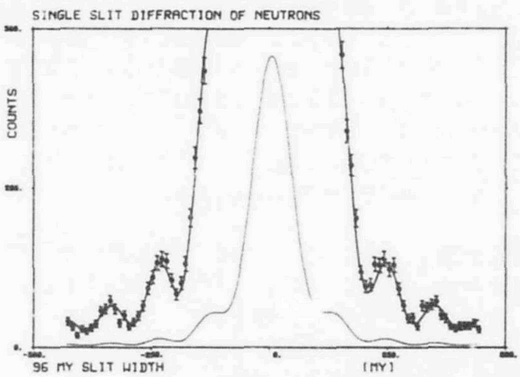

Figure 2: Diffraction pattern of very cold neutrons at a 96 μm wide absorbing slit. The abscissa is the scanning slit position and it runs from -500 to +500 μm, the ordinate runs from 0 to 500 counts. The data collecting time was 192 minutes per point.

experimental result. In order to demonstrate in detail the agreement with theory (solid line), only the wings of the diffraction pattern amplified by a factor of ten are shown. The solid line was fitted to the central maximum.

A specific class of possible experiments results, whenever an alternative nonlinear theory is developed far enough to result in detailed experimental predictions. This holds for example for the nonlinear Schrödinger equation proposed by Bialynicki-Birula and Mycielski who added a term $b.\ln|\psi|^2$ to the linear Schrödinger equation /5/. Study of the Fresnel diffraction at an absorbing edge /8/ did provide an upper limit $b=3.3\times10^{-15}$ eV. Due to the 1/E dependence of the effect, future experiments with 100Å neutrons should result in an improvement of about two orders of magnitude.

The low speed of very cold neutrons is of distinct advantage for experiments studying the effects of time-varying fields or of moving matter. In the neutron Fizeau experiment, being of the latter type, a phase shifter plate is moved in the interferometer. It is found, that whenever the neutron optical potential is wavelength independent, the Fizeau effect depends only on the motion of the phase shifter surfaces /9/. This result is a consequence of the relativistic transformation properties of the wavefunction. A most interesting consequence of these considerations is, that the neutron inside a moving plate has a frequency differing by $\Delta\omega = -(V/\hbar)(v/v_n)$ from that in the vacuum. Here, V is the neutron optical potential and v is the phase shifter's speed parallel to the neutron speed v_n. The resulting phase shift $\varphi_{Fiz.} = -kD(V/2E)(v/v_n)$ for a phase shifter with thickness D is proportional to 1/E and was first measured with 20Å neutrons /10/. The prediction of zero phase shift for matter moving parallel to its boundaries, which has also found experimental verification /11/, has recently been shown to be an approximation /12/. Particularly, due to mutiple scattering the neutron optical potential could still be slightly velocity dependent even with a constant scattering length. The predicted effect is largest in the very cold neutron region.

A related experimental situation arises, if some interaction is switched on and off over a larger region of space, such that the neutron does not experience any spatial potential boundaries, i.e. no forces. For the electron, this is the case for the electric Aharonov-Bohm effect /13/ which, due to experimental difficulties has not yet been verified. Specifically, if the potential is V, the Aharonov-Bohm phase shift is $\varphi_{AB} = -\frac{1}{\hbar} V(t) \cdot dt$ which is non-dispersive. Thus, no measurement performed on the individual beams could reveal which of the beams was subject to the time-dependent potential.

We note two connections of this to the neutron case. Firstly, that part of the Fizeau phase shift which is due to the frequency change is also dispersion free. Secondly, by using properly switched time-dependent magnetic fields, a neutron analog could be performed /14/. In order to render not even the torque on the neutron detectable either unpolarized neutrons or neutrons polarized in an eigenstate of the magnetic field should be used. A possible experimental setup for very cold neutrons is shown in Figure 3 where the time-dependent magnetic field is

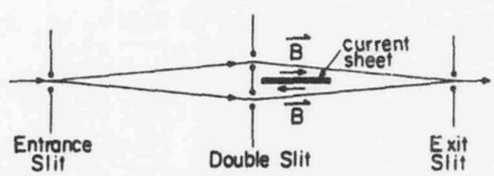

Figure 3: A possible neutron analog to the electric Aharonov-Bohm effect.

generated by a time-dependent current through a current sheet arranged between the beams of a double slit experiment. Such an experiment is clearly feasible since for very cold neutrons and a current sheet of some 10 cm length, magnetic fields in the range of a few Gauß switched with Kilohertz frequencies suffice. It will be interesting to demonstrate the property, that in such an experiment the phase shift is nondispersive. This can be done by contrasting it with a static experiment using the same field strength and demonstrating, that for large enough fields the interference contrast vanishes in the static case only.

Interestingly, there exist also analogs to the static Aharonov-Bohm case. One possible case arises in experiments searching for unknown gauge-type interactions of the neutron. Specific experiments were first proposed by Wu and Yang /15/ in order to search for a possible long-range non-Abelian interaction tied to the conservation of isospin. In analogy to the electron case where an electron current is setup between the arms of an electron interferometer, in the neutron case an isospin current has to be set up inside the neutron interferometer (Figure 4).

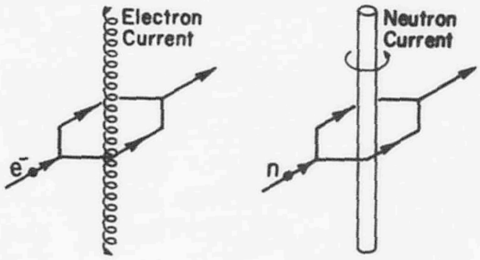

Figure 4: Principle of a neutron Aharonov-Bohm experiment searching for an unknown gauge interaction of the neutron (right) and an electron Aharonov-Bohm setup (left).

This is most easily done by inserting a Uranium rod which has a high net isospin into a neutron interferometer and spinning it rapidly. An experimental search /16/ based on that proposal with a perfect crystal interferometer gave a null result which implies that any non-Abelian gauge interaction connected to isospin is certainly smaller than $5x10^{-15}$ of the electromagnetic one for ranges of millimeters and more. It has been proposed by Shapiro /17/ that this limit could be improved by using a very cold neutron interferometer mainly due to the larger area available then between the beams.

It was pointed out above, that a significant feature of the Aharonov-Bohm effects is the dispersion-free phase shift. We note therefore that the neutron spin-orbit interaction is due to a Hamiltonian $\vec{\mu}\cdot(\vec{k}x\vec{E})$ which is inversly proportional to the neutron wavelength. This implies again a dispersion-free phase shift for a neutron passing the electric field of a charged wire arranged in the topology of Figure 4. It has been poited out by Aharonov and Casher /18/ that this analogy to the Aharonov-Bohm effect is not coincidental, since a Lagrangian can be constructed which has both effects as its consequence. Due to the non-dispersiveness of this effect the advantage of very cold neutrons does not stem from their speed but from the possibility of having larger area interferometers permitting higher electric charge to be arranged between the interferometer beams.

So far I have not discussed the possible technological developments for very cold neutrons. As an example I point out that a most promising avenue for very cold neutron interferometry is to use sinusoidal phase gratings as the coherent beam splitters. Such gratings would be based on the successful tests of Fresnel lenses for very cold neutrons /19/. Their usefulness for interferometry was demonstrated by the development of a Billet-type split-lens interferometer /20/. Most recently, in a remarkable achievement, Ioffe, Zabiyakin and Drabkin /21/ could construct an interferometer for 3.15 Å neutrons based on diffraction gratings operating in the reflection mode.

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References

/1/ U.Bonse and H.Rauch (Eds): Neutron Interferometry, Oxford University Press, Oxford, 1979.
/2/ H.Rauch in 'Foundations of Quantum Mechanics', S.Kamefuchi et al. (Eds), Phys.Soc.Japan, Tokyo, 1984, p. 277.
/3/ A.Steyerl, 'Neutron Physics' p.57, Springer Tracts in Modern Physics, Vol. 80, Springer-Verlag, Berlin, 1977.
/4/ R.Gaehler, J.Kalus and W.Mampe, J.Phys.E 13,546(1980).
/5/ P.Pearle, Phys.Rev. D13,857(1976) and D29,235(1984).
/6/ A.Zeilinger in 'Quantum Concepts in Space and Time', R.Penrose and C.Isham (Eds), Oxford University Press (in press).
/7/ A.Zeilinger, R.Gähler, C.G.Shull and W.Treimer, in 'Neutron Scattering', Amer.Inst.Phys.Conf.Proc. No. 89, p.93.
/8/ R.Gähler, A.G.Klein and A.Zeilinger, Phys.Rev. A23,1611(1981).
/9/ M.A.Horne, A.Zeilinger, G.I.Opat and A.G.Klein, Phys.Rev. A28,1(1983).
/10/A.G.Klein, G.I.Opat, A.Cimmino, A.Zeilinger, W.Treimer and R.Gähler, Phys.Rev.Lett. 24, 1551(1981).
/11/M.Arif, H.Kaiser, S.A.Werner, A.Cimmino, W.A.Hamilton, A.G.Klein and G.I.Opat, Phys.Rev. A31,1203(1985).
/12/V.F.Sears, Phys.Rev. A32,2524 (1985).
/13/Y.Aharonov and D.Bohm, Phys.Rev. 115,485(1959).
/14/A.Zeilinger, J.physique 45,C3-209(1984).
/15/T.T.Wu and C.N.Yang, Phys.Rev. D12,3845(1975).
/16/A.Zeilinger, M.A.Horne and C.G.Shull in 'Foundations of Quantum Mechanics', S.Kamefuchi et al. (Eds), Phys.Soc.Japan, Tokyo, 1984, p. 289.
/17/I.S.Shapiro, Pis'ma Zh.Eksp.Teor.Fiz. 35,39(1982).
/18/Y.Aharonov and A.Casher, Phys.Rev.Lett. 53,319(1984).
/19/P.D.Kearney, A.G.Klein, G.I.Opat and R.Gähler, Nature 287, 313(1980) and A.G.Klein, P.D.Kearney, G.I.Opat and R.Gähler Phys.Lett. 83A,71(1981).
/20/A.G.Klein, P.D.Kearney, G.I.Opat, A.Cimmino and R.Gähler, Phys.Rev.Lett. 46,959(1981).
/21/A.I.Ioffe, V.S.Zabiyakin and G.M.Drabkin, Phys.Lett. 111,373 (1985).