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SYMMETRY VIOLATIONS AND SCHWINGER SCATTERING IN NEUTRON INTERFEROMETRY

A. Zeilinger*, M.A. Horne** and H.J. Bernstein+

Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

Résumé - L'interférométrie à neutrons peut être utilisée pour mesurer directement certains déphasages dus à la diffusion. A l'aide des neutrons polarisés la phase résultant de l'interaction spin-orbite peut être déterminée directement. En principe les interactions violant les invariances P et T produisent des effets analogues, quoique des améliorations importantes de la précision de la méthode de mesure soient nécessaires pour leurs observations. Une amélioration possible de cette dernière en utilisant la résonance entre la précession de Larmor et la "pendellösung" est discutée.

Abstract - Neutron interferometry can be utilized to measure directly certain scattering phases. With polarized neutrons the spin-orbit scattering phase could thus directly be determined. In principle, P and T violating interactions lead to analogous effects, though significant sensitivity improvements are necessary for their observation. A possible enhancement by a resonance between Larmor precession and pendellösung is discussed.

Hitherto perfect crystal neutron interferometry has led to numerous beautiful experiments measuring the change of the phase of the wave function due to matter or fields acting on the neutron essentially while on flight between the crystal plates. In contrast, the possible phase change of the neutron wave due to the individual scattering event in the crystal plates themselves has found little attention, though it had been recognized from the early days of Ångstrom wave interferometry on, that these methods could in principle lead to a possible direct solution of the phase problem in crystallography. The idea there is to substitute the third crystal plate in the standard Laue-case three-crystal interferometer by a plate of the scatterer whose scattering phase is to be determined. Then it follows, that the amplitude of, say, the forward wave behind the interferometer is given as

$$u(0) \propto V(\vec{G})\, V'(-\vec{G}) + V(\vec{G})\, V(-\vec{G}) \tag{1}$$

where $V(\vec{G})$ is the Fourier transform of the neutron-crystal interaction potential appropriate for the diffracting G-planes. Unprimed quantities denote scattering in the interferometer crystal and primed quantities denote the unknown crystal. Restricting our analysis to non-absorbing crystal, we may now write

$$V(\vec{G}) = |V(\vec{G})|e^{i\varphi},\quad V(-\vec{G}) = |V(\vec{G})|\; e^{-i\varphi} \tag{2}$$

and

$$V'(-\vec{G}) = |V'(\vec{G})|/e^{-i\varphi'}\; e^{i\vec{G}(\vec{R}-\vec{R}')}. \tag{3}$$

In the latter equation, the first phase factor is the one to be determined, while in the second one $\vec{R}$ is a position vector of a lattice point in the interferometer crystal and $\vec{R}'$ is one for the unknown crystal. Thus, this latter term describes the effect of the relative translational position of these crystals. For Eq. (2) we also

Permanent addresses :
*Atominstitut der Oesterreichischen Universitaeten, Schuettelstrasse 115, A-1020 Wien, Austria
**Stonehill College, North Easton, MA 02356, U.S.A.
+Hampshire College, Amherst, MA 01002, U.S.A.

had to assume, that the lattice constants of the two crystals are equal, which feature greatly reduces the applicability of the method. The intensity of the forward beam is therefore

$$I(0) \propto 1 + \cos\,(\varphi - \varphi' + \vec{G}\cdot(\vec{R}-\vec{R}')). \tag{4}$$

This intensity is dependent on the phase difference $\varphi-\varphi'$ between the two reflections. Unfortunately it is also quite sensitive to the relative positioning of the crystals on a fractional Ångstrom scale. This latter feature together with the requirement of equal lattice constants severly limits the applicability of the method. It is important to note, that in a standard Laue-case three-crystal interferometer these conditions are met, since all three crystal plates are cut out of the same crystal. Yet Eq. (4) seems to suggest, that in that case the phase difference $(\varphi-\varphi' + \vec{G}\cdot(\vec{R}-\vec{R}'))$ vanishes in a trivial sense. We also note that then the assumption inherent in Eq. (1) that $|V(0)| = |V'(0)|$ and $|V(\vec{G})| = |V'(\vec{G})|$ are fulfilled. If these assumptions would not hold more complicated relations would follow, which are not necessary for the present paper.

It is the point of the present paper, that the method discussed above can very well be used to determine certain scattering phases, if the neutron spin is brought into play. To discuss this case we consider a non-magnetic Laue-crystal (Fig. 1) illuminated by two equally bright, coherent plane waves ψ_1 and ψ_2 of equal amplitude whose

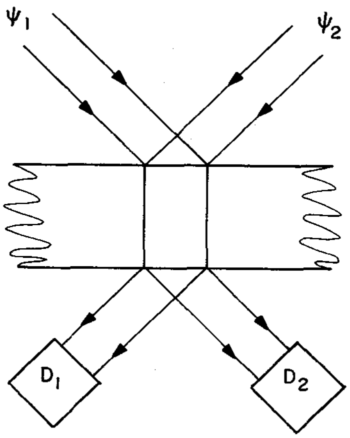

Fig. 1: Laue-case crystal plate with two Bragg waves ψ_1 and ψ_2 incident with equal amplitude and with their phase adjusted such that the intensities registered in the detectors D_1 and D_2 is equal.

wave vectors satisfy the Bragg condition exactly, whose spins are oriented normal to the scattering plane and whose relative phase is adjusted such, that the detectors D_1 and D_2 register equal intensity. We then raise the following question: "If the spin of the illuminating radiation is now flipped without introducing any shift in the relative phase of ψ_1 and ψ_2, will the intensities in the detectors D_1 and D_2 change, i.e., does spin reversal itself produce a fringe shift?"

Analyzing this case, we first note, that the spin is flipped around the same axis in both beams. Thus we avoide any phase factor due to the flipping field itself /1/. Yet, in the presence of Schwinger spin-orbit scattering, the potential coefficients $V(\vec{G})$ are complex quantities even if all other contributions are real

$$V(\vec{G}) = V(-\vec{G})^* = V(\vec{G})\, e^{i\varphi_{SO}} \tag{5}$$

because the spin-orbit scattering length is purely imaginary /2/

$$b_{SO} = i\, b_F\, Z(1-f) \cot\Theta_B\; \vec{\sigma}\cdot\hat{n} \tag{6}$$

where $b_F = -1.468 \times 10^{-3}$ fm is the Foldy scattering length /3/, Z is the charge number of the nucleus, f is the electron form factor, Θ_B is the Bragg angle, $\vec{\sigma}$ is the Pauli spin operator and $\hat{n}$ is a unit vector normal to the scattering plane. The answer to our question above follows immediately from Eqs. (5) and (6). Focussing, e.g., on the beam leading to detector D_1, we note that its partial amplitude coming from ψ_1 will suffer a phase change of $2\varphi_{SO}$ merely due to the spin flip. Hence the superposition with the forward scattered part of ψ_2 which does not experience such a phase change will lead to an observable change of intensity.

We propose an experiment using a three-crystal interferometer (Fig. 2), since the technology of polarized neutron interferometry is well developed by now /4/. The

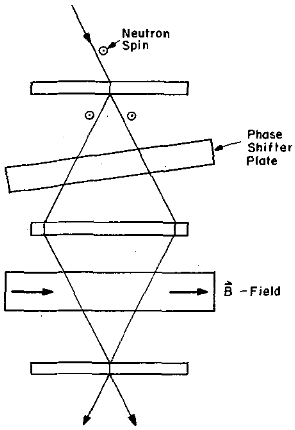

Fig. 2: Proposed experimental arrangement for a direct measurement of the spin-orbit scattering phase using a Laue-case three-crystal interferometer. The B-field is arranged such, that its phase shift effect on the two interferometer beams is identical.

nuclear phase shifter would be used to get the interferometer at maximum phase sensitivity and a magnetic field would flip the spins between the second and the third crystal plate. Thus, if varying in such an experiment the magnetic field strength, a variation of the intensities of the beams behind the interferometer with the periodicity of the Larmor precession will result, in contrast to the 4π-experiments where double that periodicity was observed. The contrast of the fringes will be determined by the spin-orbit scattering phase shift. We find for $2\varphi_{SO}$, i.e. the phase shift due to a complete spin flip, and Si (220) reflection values of 1.85×10^{-1}, 3.66×10^{-2} and 1.79×10^{-2} radians for neutrons of wavelength 0.1, 0.5 and 1.0 Ångstrom, respectively. We further note, that the sensitivity could be improved by another factor of two, if a flipping field would also be employed between the first two crystal plates. If the crystal plates are sufficiently thin, such a field could extend all over the interferometer crystal.

Another spin-dependent effect results if the neutron carries an electric dipole moment μ_e. This has explicitely been used by Shull and Nathans /5/ in a search for a neutron EDM using absorbing crystals. The corresponding scattering length is given as

$$b_{EDM} = i\, Ze\,(1-f)\,\frac{2m}{\hbar^2 G}\,\mu_e\,\vec{\sigma}\cdot\hat{G}. \tag{7}$$

Thus, if we had neutrons polarized parallel to $\vec{G}$, we would pick up a phase shift of only 1.1×10^{-8} radians upon spin flip both in front and behind the middle plate in an Si (220)-interferometer for $\mu_e/e = 10^{-25}$ cm. P and T violating contributions to the scattering length could also exhibit a $\vec{\sigma}\cdot\hat{G}$ dependence as proposed by Forte /6/. He would look for such a term using non-centrosymmetric crystals. We propose that a neutron experiment along the lines discussed above could also be employed in such searches. Similar comments hold for P violating terms of the form $\vec{\sigma}\cdot(\hat{n}\times\hat{G})$, which implies an arrangement of the neutron spin parallel to $\vec{h}+\vec{k}'$. The magnitude of the latter term can be estimated from the experiments measuring P violation as a spin rotation effect /7/ in the transmission of polarized neutrons. Estimation shows the resulting phase shifts to be too small for observation in an individual scattering event. A similar comment probably holds for the simultaneously P and T violating contribution /6,8/, though we are not aware of any reliable estimates of its magnitude in nuclear scattering.

As we mentioned in the discussion of the spin-orbit term, an enhancement by a factor of 2 can be achieved by flipping the spin also in front of the first crystal plate. In general, by employing n crystal plates in a zig-zag reflection manner with spin flips between each of the plates an enhancement by a factor of 2n over the phase of the individual scattering event may be achieved. For intensity optimalization the thickness of the individual crystal plates should there be just half a pendellösung length. By analogy one can then replace the multiplate arrangement by one big crystal and extend the flipping field all over that crystal. There, an analogous amplification of the phase occurs, if the magnetic field is tuned such, that the Larmor precession length equals the pendellösung length. It will be shown in a future publication, that in that case of a pendellösung-Larmor precession resonance one of the solutions of the Takagi-Taupin equations exhibits phase amplification by a factor of the order of D/Δ, where D is the crystal thickness and Δ is the pendellösung length. Using very thick crystals, amplifications of the order of 10^3 - 10^4 may thus be achievable. In a possible experimental application a non-trivial question concerns the separation of the odd-symmetry effects from Schwinger scattering which implies extremely precise alignment of the crystal in the very homogeneous magnetic field. Yet it is still not obvious, whether an integrated intensity sufficient for providing the necessary statistical accuracy is obtainable within reasonable measuring time in order to improve the present limit on the neutron EDM. The situation may be different for simultaneously P and T violating terms, where presently no experimental limit has been set.

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