Multiphoton Exchange Amplitudes Observed by Neutron Interferometry

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Polarized neutron interferometry has been used to measure the amplitudes for the exchange of up to five photons between the neutron and an oscillating magnetic field. The Rabi spin flip configuration and a configuration in which spin flip is suppressed were investigated, because they raise different questions on the conservation of angular momentum. Because of the linearity of the time-dependent interference signal in the exchange *amplitudes,* photon exchange probabilities below 1% could be resolved.

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In the interferometry with massive particles, which currently includes electrons [1], neutrons [2], several species of atoms [3], and the Na_2 molecule [4], the amplitude information available in the interference pattern has rarely been used. Exceptions are electron holography [5,6], absorption in neutron interferometry [7], and measurements of spectral distributions with electrons [8] and neutrons [9–11]. As the interference contrast is linear in the square roots of the probabilities of the two (or more) superposed states, these experiments could exploit the increased sensitivity at small probabilities. Here, we report on the use of this feature to determine the amplitudes for the exchange of several photons between the neutron and a magnetic field oscillating in time. In our setup, the neutron passes through a Mach-Zehnder interferometer and in one arm is subject to the oscillating field with which it interacts due to its magnetic moment. In the region after the field this generally results in a neutron state whose phase and spin state are periodic with the frequency of the field. Hence, for a neutron with energy E_0 and spin state $|+z\rangle$ *before* the field, the state *after* the field must be of the form [12]

$$|\psi_f\rangle = \sum_j (u_j|+z\rangle + d_j|-z\rangle)\,|E_j\rangle, \qquad (1)$$

showing the neutron in a superposition of discrete energy states. These energies are given by $E_j = E_0 + j\hbar\omega$, where ω is the angular frequency of the field. For positive j, there is a quantized transfer of energy *from* the field *to* the neutron, and *vice versa* for negative j. The amplitudes d_j and u_j take into account that this may happen with or without a neutron spin flip, respectively. Using a classical magnetic field the exchanged quanta cannot readily be named. However, for the parameter range of interest here, the quantized and the classical description of the field yield the same amplitudes u_j and d_j [13]. We can therefore speak of the exchange of photons, in analogy to the exchange of phonons in neutron scattering at vibrating macroscopic objects [14].

This raises the question of conservation of angular momentum. In a naive view, the neutron should undergo a spin flip when absorbing one photon *from,* or emitting one photon *into* the field, because the neutron has spin $\hbar/2$ and the photon has spin $\hbar$. Hence u_1 and u_{-1} should vanish. Absorption or emission of one more photon should then restore the original spin state, and therefore d_0, d_2, and d_{-2} should vanish, and so forth. In this picture a change of the neutron's energy by an even number of quanta preserves the spin state, while change by an odd number of quanta leads to a spin flip. Interestingly, this picture works when the oscillating field and the initial neutron polarization are perpendicular to each other, but it fails when they are parallel. For then the neutron may, for instance, absorb the energy of only one photon and yet keep its spin state.

While it is clear that this simple picture cannot be true, as the neutron behaves as a "dressed neutron" *in* the field [15], the mechanism of angular momentum conservation must still be different in the two field configurations. The purpose of the experiment was a quantitative determination of the various amplitudes u_j and d_j for the two configurations, and thereby—through comparison with theory—an indirect demonstration of this difference.

In the so-called parallel field configuration, the neutron crosses the spatially homogeneous field

$$\vec{B}_p(t) = \hat{z}(B_0 + B_1\cos\omega t)\,, \qquad (2)$$

which is similar to that used in measurements of the scalar Aharanov-Bohm effect [16,17]. The direction of the field remains parallel to the quantization axis of the neutron spin, hence no spin flip can occur and $d_j = 0$ for all j. The amplitudes u_j are given by the Bessel functions

$$u_j = J_j(\alpha B_1), \qquad \alpha = (\mu/\hbar\omega)\sin(\omega\tau/2)\,, \qquad (3)$$

where μ is the magnetic moment of the neutron and τ is the time of flight through the field region [12]. Note that the neutron can absorb from the field or emit into it an even as well as an odd number of photons, in each case preserving its spin state.

In the so-called perpendicular field configuration, static and oscillating field components are perpendicular to each other,

$$\vec{B}_n(t) = \hat{x}B_0 + \hat{z}B_1\cos(\omega\tau)\,. \qquad (4)$$

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When $B_1 \ll B_0$ one has the conditions of the Rabi resonance spin flip, where only one photon is exchanged [18]. This was used as a method of spin flip in earlier neutron interferometry experiments [19,20]. To facilitate the exchange of more photons in the present experiments, B_1 and B_0 were of comparable size. As mentioned above, here the exchange of an *even* number of photons preserves the spin state, and the amplitudes for emission and absorption are equal. Spin flip only occurs when an *odd* number of photons are either absorbed or emitted, and the amplitudes for emission and absorption are in general very different from each other [12,13].

A schematic diagram of the experimental arrangement at beam port C at the University of Missouri Research Reactor as shown in Fig. 1. A monochromatic beam of thermal neutrons ($\lambda = 2.35$ Å, $\Delta\lambda/\lambda = 5 \times 10^{-3}$) was produced by Bragg reflection in a vertically focusing pyrolitic graphite (PG) crystal monochromator assembly. Order contamination was eliminated by passage through a standard 5 cm long PG filter. The beam was then reflected off a vertically magnetized Fe/Si supermirror of length 50.4 cm. The angle between incident and reflected beam was 0.96°, resulting in a 2 mm wide polarized beam with a probability of the state $|+z\rangle$ of at least 0.88. The beam height at the interferometer was 6 mm. To keep the spin quantization axis well defined the vertical magnetic field was continued beyond the supermirror by means of permanent magnets and into the region of the interferometer by means of a pair of Helmholtz coils to enable control of the static field component B_0. The interferometer, made of single crystal silicon, used refraction at the 220 planes for beam splitting and recombination. The centerlines of the long parallel stretches of the two paths inside the interferometer were 21 mm apart. The phase shift between them was adjustable by means of a 1.05 mm thick Al phase plate.

The oscillating magnetic field region was placed in path I. In the parallel field configuration, the oscillating field was created by a C-shaped yoke consisting of alternating layers of 1 mm iron and 1 mm cardboard and two driving coils above and below the gap. The neutrons passed through the gap, which was 7 mm high, 14 mm wide, and measured 21 mm along the neutron trajectory. The guide field was adjusted to avoid a zero crossing of the magnetic field. In the perpendicular field configuration, the oscillating field was produced by a rectangular copper coil, already used elsewhere [20], of dimensions 16 mm × 19.5 mm through which the neutrons passed axially. It extended 19 mm along the neutron path. In both configurations the coils were cooled to within 0.02 °C of the ambient air to minimize distortions of the interferometer crystal leading to phase drifts. The coils were driven sinusoidally with 7534 Hz. The upper limit of this frequency was set by the achievable time resolution of the neutron detection scheme.

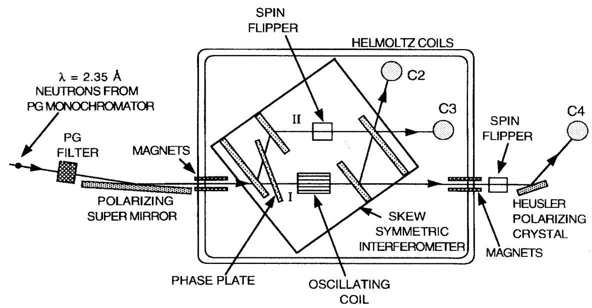

FIG. 1. Schematic layout of the experiment (not to scale). The spin flipper in path II was only present in experiments with perpendicular field configuration. Not drawn: Permanent magnets on both sides of the interferometer, which were only present in experiments with parallel field configuration.

The two beams exiting from the interferometer hit cylindrical ^{3}He detectors, with a diameter of 1.27 cm, perpendicular to their axes. The mean intensities at detectors C2 and C3 were 3.7 and 1.3 counts/s, respectively. The contrast of an interferogram obtained by rotating the phase plate was typically 50%. In order to resolve the time dependence of the interference signal, the counts in each detector were fed into a PC-based Ortec multichannel scaler card that was run synchronous to the oscillating magnetic field. Each period of the magnetic field was divided into 64 time channels, each of width 2.07 μs. The polarization after the oscillating field region was measured on the beam leaving the interferometer after the third crystal slab. That beam passed through a spin flipper and was then analyzed by a Heusler crystal, which only reflected the $|-z\rangle$ component into detector C4.

For the determination of the non-spin-flip amplitudes u_j the static spin flipper in path II was switched off, or it was not present at all, such that the probability of detecting a neutron at detector C3 was proportional to

$$||+z\rangle + e^{i\chi}|\psi_f\rangle|^2 = 1 + \left|\sum_{j=-\infty}^{N}(u_j|+z\rangle + d_j|-z\rangle)e^{-ij\omega t}\right|^2 + 2\sum_{j=-\infty}^{N}|u_j|\cos(\phi_j + \chi - j\omega t), \qquad (5)$$

where χ is the phase shift induced by the phase plate and ϕ_j are the phases of the amplitudes u_j. Counting the number of unknowns shows that magnitudes as well as phases of the u_j could be obtained from the Fourier transforms of just three runs with different settings of χ. The spin flip amplitudes d_j could be determined analogously, but the static spin flipper in path II had to be turned on.

Typical data of the normalized counts in C3 are shown in Fig. 2. Differences in detection efficiency of C2 and C3, as well as different times of flight from the exit point of the interferometer to the detectors are taken into account.

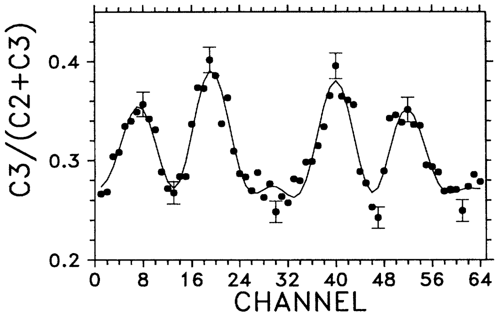

FIG. 2. One of the data sets with $B_1 = 62.8$ G of experiments with the parallel field configuration. Average counts per channel (C2 + C3): 1341. Channel width: 2.07 μs. Solid line: Reconstruction of data from Fourier spectrum up to the sixth harmonic.

The error bars indicate the statistical standard deviation. In Fig. 3 the photon exchange amplitudes obtained with the parallel field configurations are shown as a function of the strength of the oscillating field. The full lines are a least squares fit of the theoretically expected Bessel functions done simultaneously to all the data shown. The only free parameter was the scaling constant s in the argument of the Bessel functions, $J_n(s\alpha B_1)$. The error bars of the data points include the statistical standard deviation as shown in Fig. 2, the uncertainty in the different values of the phase shift χ due to slow drifts during data accumulation, and the uncertainty in the interference contrast of the interferometer. The latter is very sensitive to vibrations and temperature gradients, and the statistics of Fig. 3 suggest that this has led to a small systematic error. Of the 99 measured amplitudes shown, 45 differ from the theoretical curve by more than 1, and 10 differ from it by more than 3 standard deviations. But the general consistency between observed and predicted values of the exchange amplitudes confirms that in this configuration, indeed, an even as well as an odd number of photons can be absorbed or emitted by the neutron despite the fact that no neutron spin flip occurs. Obviously, the picture of angular momentum conservation presented above is untenable in this case.

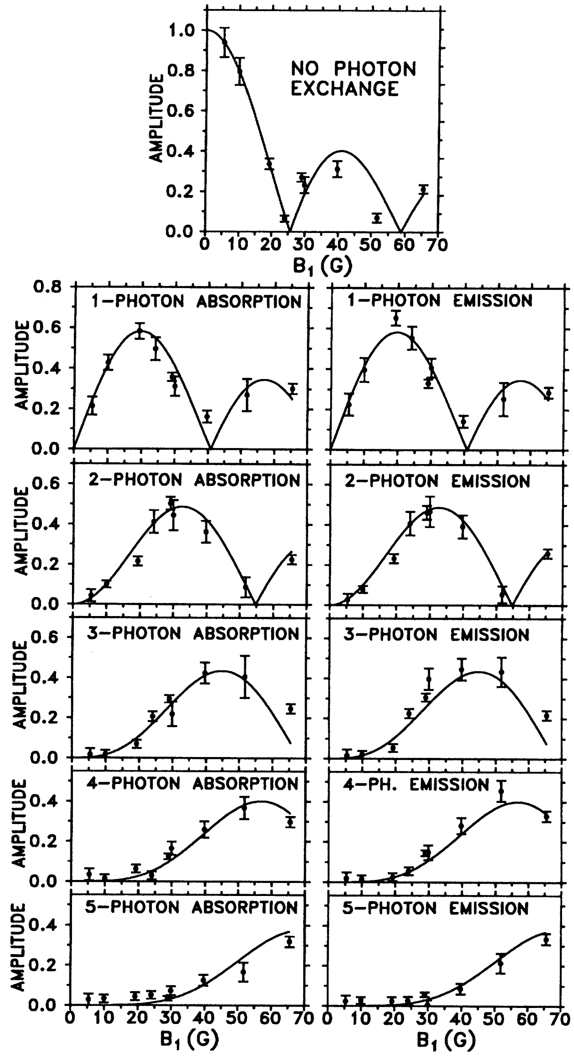

FIG. 3. Photon exchange amplitudes obtained in experiments with parallel field configuration, as a function of the oscillating field component B_1. Data are normalized such that the total exchange probability from -10 to $+10$ exchanged photons is 1.

Results of two experiments with the perpendicular field configuration are shown in Fig. 4. The panels on the left-hand side [Figs. 4(a) and 4(c)] show results with the static spin flipper off. Ideally the interference pattern then only contains amplitudes for the exchange of an even number of photons, because these processes do not lead to a spin flip. The amplitudes for emission and absorption should be equal. The panels on the right-hand side [Figs. 4(b) and 4(d)] depict the results with the static spin flipper switched on. Here, only photon exchange processes accompanied by a spin flip and thus involving only an odd number of photons should ideally be contained in the interference pattern. The amplitudes for emission and for absorption need not be equal. It can be seen that these predictions are reasonably well fulfilled by the data. The deviations, as seen in the nonvanishing amplitudes for exchange of an even number of photons in the panels on the left, and for exchange of an even number of photons in the panels on the right, can be attributed to nonperfect realization of the desired field configuration: At the site of the oscillating coil the guide field had a small horizontal component (<3), and in Figs. 4(b) and 4(d), a nonperfect static spin flip in path II led to a contribution in the interference pattern containing both flipped and nonflipped components of the state vector of path I. The open circles and triangles in all panels of Fig. 4 show the results of two simulations in which the field in the coil region was assumed spatially homogeneous and sharply bounded, and the values of B_0 and B_1 were taken to be the experimentally measured fields at the coil center. The length of the region was taken as 22.3 mm (open circles) and 24.5 mm (triangles)

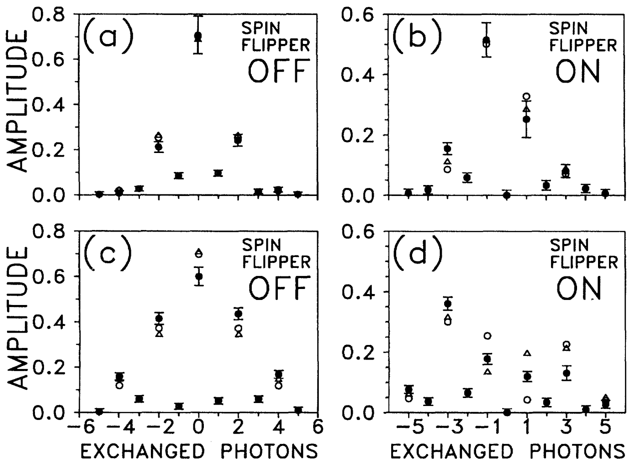

FIG. 4. Photon exchange amplitudes for two different experiments with perpendicular field configuration. Closed circles indicate experimental data; open circles and triangles show results of theoretical simulations. Positive signs and negative signs correspond to photon absorption and photon emission, respectively. Probability of spin flip in oscillating field region as obtained in the simulations for experiment of upper panels (a),(b): 0.37; for experiment of lower panels (c),(d): 0.21. Field values for experiment of upper panels: $B_0 = 9.9$ G, $B_1 = 14.8$ G. For experiment of lower panels: $B_0 = 11.6$ G, $B_1 = 25.8$ G.

instead of the actual 19 mm. The agreement with the data is quite good, except in Fig. 4(d), where the simulation showed that the amplitudes for emission of a photon (-1) and for absorption of a photon $(+1)$ are very sensitive to small changes of coil length. The experimental data seem to be an average over different effective coil lengths.

The overall good agreement of theoretical and observed amplitudes for photon exchange between the neutron and the oscillating magnetic field shows the impossibility of the simple picture of conservation of angular momentum for the parallel field configuration. Furthermore, it suggests that time-resolved neutron interferometry may be useful in the investigation of dynamical processes, e.g., in solids or liquids.

It should also be noted that the low frequency and fields used in the present experiments permit an understanding of the interference signal without the concept of energy exchange. It is sufficient to trace the accumulation of phase of the two spin components *inside* the coil. *After* the coil a neutron state with energy E_0 and one with energy $E_0 + \Delta E$ to first order in $\Delta E/E_0$ acquire the same phase over a given path length, such that for small ΔE there is no further contribution to the phase shift between the two interferometric paths.

With respect to alternative ways of measuring small changes of energy, as, for instance, by high resolution spectroscopy, it should be noted that such methods require the neutron's change in energy to be larger than the energetic width of the incident beam, and are only sensitive to the probability of a specific exchange process [14]. The interferometric method, on the other hand, is directly sensitive to the quantum mechanical amplitude of a process, and there is no lower limit for the achievable energy resolution.

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