Dressed Neutrons

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When neutrons are exposed to a large number of electromagnetic quanta of arbitrary frequency their spin rotation about a static magnetic field can be suppressed completely. Further, natural-linewidth level-crossing signals in the neutron polarization can be produced. These observed effects are interesting also in connection with neutron electric-dipole-moment and neutron oscillation experiments. They are described in the dressed-particle formalism developed in atomic physics. We were able to reconstruct the dressed-neutron energy-level diagram experimentally.

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Neutrons interacting simultaneously with a large number of electromagnetic quanta may be called dressed neutrons. We chose this name in analogy to the dressed-atom concept developed in atomic physics a number of years ago.[1] After second quantization, the total system "neutron+static magnetic field+radio-frequency (rf) quanta" turns out to have a rich energy-level diagram with an infinite number of level crossings and anticrossings. These crossings give rise to several interesting effects, such as the appearance of level-crossing signals with natural linewidths in the neutron polarization, or the suppression of the neutron's magnetic g factor, effects which possibly find interest in slow-neutron measurement technology.

Slow neutrons turn out to be ideal candidates for the study of dressed-particle effects: In our context neutrons can be regarded as perfect two-state systems with no internal structure, they allow very sensitive measurements of energy shifts[2] as small as 10^{-20} eV, and last but not least, dressed-neutron spin-rotation experiments are conceptually much simpler and more transparent than the corresponding steady-state experiments with atoms. Dressed-neutron effects show up when static and oscillatory fields have comparable sizes; therefore, the experiments described here cannot be done with conventional NMR or ESR probes, which need static magnetic fields much larger than available rf fields.

Figure 1(a) shows the energy-level diagram of a dressed-particle system with spin $S=\frac{1}{2}$, as discussed in Ref. 1. Plotted are the eigenvalues E of the second-quantized Hamiltonian

$$H=H_M+H_{\text{ph}}+H_{\text{int}}$$
$$=\hbar\omega_0 S_z+\hbar\omega a^\dagger a+\lambda S_i(a+a^\dagger) \quad (1)$$

in dependence upon the static magnetic field B_0. The term H_M leads to the usual neutron Zeeman splitting represented by the dashed lines of Fig. 1(a), with the Larmor frequency $\omega_0=\gamma B_0$, the gyromagnetic ratio $\gamma=g\mu_N/\hbar$, the particle's magnetic g factor, and the nuclear magneton μ_N. The term H_{ph} adds to this the energies $n\hbar\omega$ ($n=0,1,2,\ldots,$) of a number n of rf photons of frequency ω, with the creation and annihilation operators $a^\dagger$ and a. Finally, the term H_{int} represents the cou-

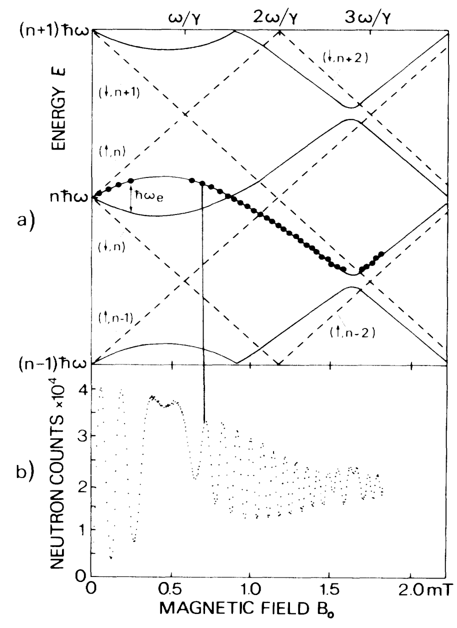

FIG. 1. (a) Energy-level diagram of the dressed-neutron system for $B_1=0.1$ mT. Dashed lines: Zeeman splitting (from H_M) at photon field energies $n\hbar\omega$ (from H_{ph}). Solid lines: The energy levels repel each other because of the coupling (from H_{int}) between the neutron and the photon field. (b) Dressed-neutron spin-rotation pattern; from the measured eigenfrequencies the experimental energy eigenvalues in (a) are reconstructed, as described in the text. The error bars are of the same order as the size of the points.

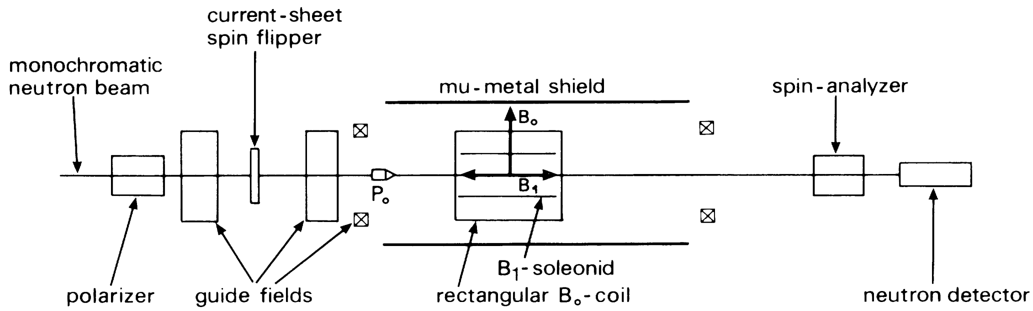

FIG. 2. Neutron-beam equipment for the spin-rotation measurements of Figs. 1 and 3.

pling of strength $\lambda=\hbar\omega_1/2\bar{n}^{1/2}$ between the rf photons and the particle's magnetic moment, with $\omega_1=\gamma B_1$, the rf magnetic field amplitude B_1, and the average number $\bar{n}$ of rf photons in the field; S_i is the component of the particle's spin angular momentum along B_1. In Fig. 1(a) the direction of the linearly oscillating rf field B_1 was chosen perpendicular to the direction of B_0, and $S_i=S_x$.

At field values $B_0=\omega/\gamma$, $3\omega/\gamma$, and $5\omega/\gamma$ the energy levels repel each other (anticrossing) because $H_{\rm int}\propto B_1$ leads to a mixing of spin states which in turn leads to the well-known occurrence of 1-, 3-, 5-, . . . quanta spin-resonance transitions.

We did altogether three experiments on the dressed-neutron system.

(1) In a first experiment we directly reconstructed the dressed-neutron energy-level diagram of Fig. 1(a) by measuring the *eigenfrequencies of the dressed-neutron system* by means of neutron-spin rotation. We used the simple neutron-beam setup[3] shown in Fig. 2. Cold neutrons from a neutron guide at the high-flux reactor of the Institut Laue-Langevin are monochromatized by Bragg reflection at a velocity of $v=500$ m/s, polarized to 97% with a supermirror neutron polarizer, and passed axially through a Mumetal cylinder, with the initial neutron polarization along the beam axis. Within the Mumetal shield the neutrons nonadiabatically enter and leave the spin-rotation region of length $L=30$ cm, where they interact with a transverse static magnetic field B_0 and an oscillating axial field B_1. The neutron polarization subsequently is analyzed with a second supermirror.

The polarization in this experiment is expected to vary as $P=P_0\cos\omega_e T$. The eigenfrequency ω_e is a function of B_0, B_1, and ω, and the time of flight in the B_0-field region $T=L/v$ is a constant. Without the rf field we have $\omega_e=\omega_0=\gamma B_0$ and measure the usual spin-rotation pattern which defines the slope of the dashed line of Fig. 1(a). When we switch on the rf field with $B_1=0.10$ mT and $\omega=113$ kHz we observe the spin-rotation pattern of Fig. 1(b). From the minima and maxima of this pattern, where $\omega_e T=n\pi$ (see vertical line in Fig. 1), we derive the eigenfrequencies $\omega_e(B_0)$, insert the values $\hbar\omega_e$ into the energy-level diagram [Fig. 1(a)], and find good agreement with the energy-level diagram obtained by diagonalization of the (suitably truncated) dressed-neutron Hamiltonian (1).

(2) *The g factor of the dressed neutron* determines the low-field spin-precession frequency. It need not be the same as the g factor of the free neutron, as is known from Hanle-effect and hyperfine-splitting measurements with dressed atoms.[1,4] In a second experiment we therefore measured low-field neutron spin-rotation patterns for several values of the rf-field strength B_1. As shown in Fig. 3, neutron spin rotation slows down with increasing rf-field strength B_1, comes to a complete stop for a certain value of B_1, and starts moving backwards[5] at still higher values of B_1. These effects are nonresonant, as they can in principle be produced with any value of the frequency ω. Figure 4 shows the measured values of $g_{\rm dressed}/g_{\rm free}$ which follow a Bessel function $J_0(\omega_1/\omega)$ as predicted by theory.[1]

This observed change in neutron spin-rotation frequency must be excluded as a source of error, for instance, in high-precision neutron magnetic-moment measurements,[6] where a 50-Hz background field of 1-nT amplitude could produce an observable effect.

(3) When a neutron beam is polarized transversely with respect to B_0, then both spin states "up" and "down" are populated coherently. Therefore, at those field values of Fig. 1 where two energy levels happen to be degenerate, one can expect interference signals in the neutron polarization to show up, also called *level-crossing signals*. In the case where the rf field B_1 is applied parallel to B_0 [in which case $H_{\rm int}=S_z(a+a^\dagger)$ merely introduces an overall shift of the Zeeman energy levels, but does not lead to a coupling of different neutron spin states], we find these steady-state[7] signals in the transverse neutron polarization to be

$$P=P_0\sum_{n=-\infty}^{+\infty}J_n^2\left(\frac{\omega_1}{\omega}\right)\int_0^\infty\rho(T)\cos(\omega_0-n\omega)T\,dT.$$

The oscillatory level-crossing signals appear at the field values where the dashed lines of Fig. 1(a) cross each other, that is, at $\omega_0=0$ (Hanle signal), $\omega_0=\omega$, 2ω, 3ω, etc. Their width is determined only by the neutron's time of flight T through the spin-precession region. The envelope of the signals is given by the Fourier transform of the neutron's time-of-flight spectrum $\rho(T)dT$, and their

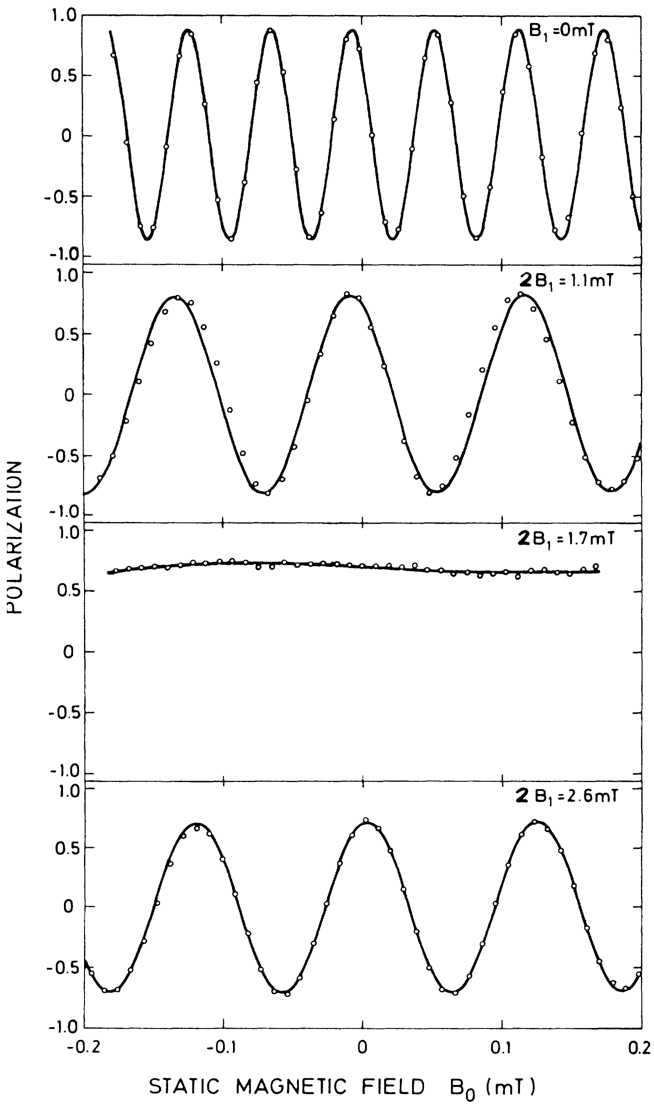

FIG. 3. Spin-precession measurements with dressed neutrons. At the critical rf-field strength $2B_1 = 1.7$ mT the g factor of the dressed neutron vanishes, and neutron spin-precession disappears.

amplitude by the square of the nth-order Bessel function $J_n(\omega_1/\omega)$.

Figure 5 shows the results of our third experiment, done with a polychromatic beam of cold neutrons of 100 m s^{-1} average velocity. Because of low neutron intensities we did not optimize the amplitude of the level-crossing signals, but wanted only to show their existence.

The position of the signals is also sensitive to the interaction of a neutron electric dipole moment with an electric field. Dressed-neutron level-crossing spectroscopy may thus be considered as an alternative to the Ramsay separate oscillatory field method applied so far in electric dipole moment searches.[2]

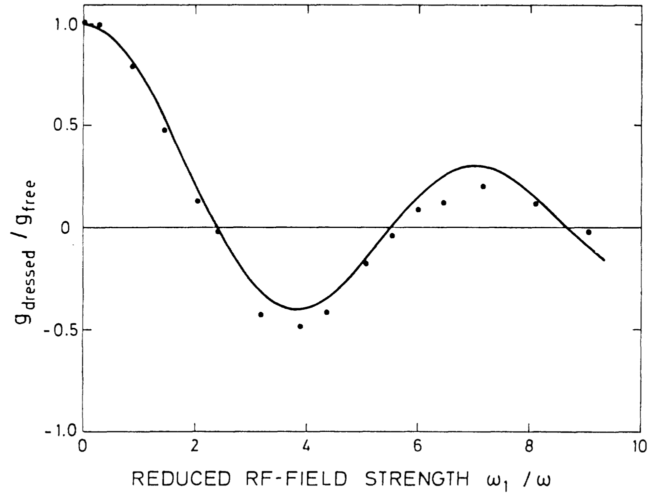

FIG. 4. Variation of the dressed-neutron's g factor with rf-field strength ($\omega_1 = \gamma B_1$).

Dressed-neutron effects also merit discussion in the context of current neutron-antineutron oscillation searches.[8] These oscillations are suppressed by the earth's magnetic field, which lifts the degeneracy between neutrons and antineutrons. Can the dressing of neutrons reestablish this degeneracy? Suppression of the effective magnetic interaction by making $g_{\text{dressed}} = 0$ does not help here, because the neutron oscillations are also decoupled in the process. However, one can indeed partly reestablish the neutron oscillation process by modulating B_0 so as to reach a level-crossing position in the energy diagram; there neutron and antineutron states will again be degenerate. This problem has recently been discussed in detail in the literature[9-11] on a semiclassical basis, which is perfectly adequate. However, we feel that the discussion of the problem in terms of the dressed-neutron level-crossing picture gives more physical insight.

If one should ever want to use this method of B_0-field suppression in a neutron-oscillation search it will be necessary to provide experimental proof that all requirements on B_0, B_1, and ω were met during the run. This

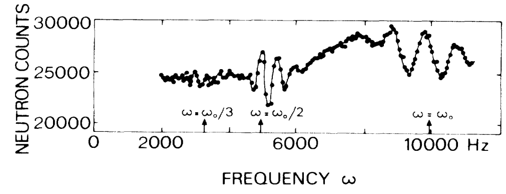

FIG. 5. Level-crossing signals in the neutron's transverse polarization, measured as a function of the rf frequency ω. The signals appear at the crossing points of the dashed lines of Fig. 1(a), that is, $\omega = \omega_0$, $\omega_0/2$, $\omega_0/3$.

can be done most convincingly by repetition of the neutron level-crossing experiment described in this article. If the narrow neutron signals can be observed, then the apparatus is ready for a neutron-oscillation search.

In conclusion, we have shown that the second-quantization energy-level diagram can be reconstructed from polarized-neutron spin-precession measurements, that a static magnetic interaction of the neutron can be decoupled by irradiation with a large number of radio-frequency quanta of rather arbitrary frequency, that natural-linewidth dressed-neutron level-crossing signals can be observed via the neutron polarization, and that all these effects deserve discussion in the context of a number of neutron experiments.

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