Spontaneous Polarization of Particles

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Unpolarized particles with spin may spontaneously polarize during their flight through a resonant cavity, due to their interaction with the cavity's quantized radiation field. This effect, of purely electromagnetic origin, could, if not recognized as such, be mistaken for a parity violating weak interaction effect. For a better understanding of this effect we have simulated it, as well as the related quantum field effects of collapse, revival, and hidden coherence, with a beam of polarized neutrons and a set of classical magnetic fields.

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The two-level atom coupled to a quantized radiation field is the subject of many recent investigations in the field of quantum optics. In the rotating wave approximation this system is described by the Jaynes-Cummings model [1]. The model predicts a number of interesting effects, like a collapse [2,3] and, later on, revivals [3,4] of the Rabi oscillations, and "hidden coherences" [5]. Experimentally a first revival of an atomic wave function was observed several years ago with the one-atom maser [6]. Recently, it was also pointed out [5] that this two-level atom will, in the course of time, spontaneously develop a perfectly coherent state which is completely independent of the initial state of the atom (and also independent of the separation of the two levels).

It is well known that the two-level atom in a radiation field is homomorphic to a spin one-half particle precessing in magnetic fields [7], for instance in a magnetic resonance setup. When the effect of spontaneous coherence quoted above is translated into the spin precession picture, it means that a spinning particle in a resonator will develop a large polarization which is independent of the initial spin state of the particle. Hence this polarization also appears when the initial state of the particle is unpolarized. We call this process the spontaneous polarization of particles. The peak polarization achievable is independent of the size of the Zeeman splitting. The angular momentum balance in this process is provided by the rotating quantized fields.

This electrodynamic effect of spontaneous polarization is interesting in its own right. But it also deserves investigation in a different context: The spontaneous rise of a polarization in an initially unpolarized system is commonly regarded [8] as an indicator of parity nonconservation (PNC), which is a unique feature of the weak interaction. Similarly, when a spin points into a direction which is different from the one expected classically then this may also be due either to PNC [9] or to electromagnetic (hence parity conserving) quantum field effects.

These general considerations incited us to explore the quantum radiation problem, which usually is the domain of quantum optics, with the means at our hands: A free neutron in a *classical* magnetic field is one of the simplest systems in physics. Still, it allows one to study a number of elementary and far-reaching concepts and phenomena in a very transparent way, like spinor rotation [10] and spinor superposition [11], Berry's phase [12], the "dressing" of particles [13], or bistability [14]. So we wondered whether we could also simulate the "grainy" character of quantized fields, such as to reproduce the quantized field effects mentioned above with a beam of polarized neutrons interacting solely with classical fields, in order to elucidate the intricate mechanism of the particle-field interaction with a simple and transparent model. Of course, we cannot expect to reproduce all quantized field effects with one set of classical fields: A particle interacting with quantized fields is just a small subsystem of a large coupled many-particle system and cannot be treated in an isolated way.

The Jaynes-Cummings Hamiltonian for a particle with gyromagnetic ratio γ in a static magnetic field B_0 reads

$$H=\tfrac{1}{2}\hbar\gamma B_0\sigma_z+\hbar\omega a^\dagger a+\hbar g(a^\dagger\sigma_-+\sigma_+a)\,, \qquad (1)$$

with Pauli matrices σ, creation and destruction operators $a^\dagger$ and a for photons of frequency ω, and the photon number operator $a^\dagger a$ (with eigenvalues $n=0,1,2,\ldots$). The magnetic coupling constant g for the particle-photon interaction is related to the classical rf amplitude B_1 as $\gamma B_1=2g\bar{n}^{1/2}$. The average photon number $\bar{n}$ can be eliminated by setting $\bar{n}\hbar\omega=B_1^2V/2\mu_0$, with the resonator volume V. In resonance, $\omega=\gamma B_0$.

In the following we shall make a number of statements on the solutions of (1) and look how they can be simulated by our neutron system. The first, very simple statement is as follows.

(i) The (longitudinal) polarization $\langle\sigma_z\rangle$ of an ensemble of particles, initially in the "up" state and interacting with a resonant quantized radiation field, behaves as if each particle was independently precessing about one of the discrete classical magnetic fields $B_1(n)=(2g/\gamma)\sqrt{n+1}$.

For instance, for a Glauber coherent photon state with Poissonian distribution of photon number n the solution of (1) for an atom initially in the upper state reads [4]

$$\langle \sigma_z(t) \rangle = e^{-\bar{n}} \sum_{n=0}^{\infty} \frac{\bar{n}^n}{n!} \cos(2g\sqrt{n+1}\,t) . \tag{2}$$

Statement (i), however, is valid for any weight distribution $P(n)$ of the photon number n.

In the one-atom maser a two-level atom in the upper state enters the resonator at $t=0$, interacts with the quantized field during the time of passage t, and leaves the resonator for final state analysis. In our simulation experiment a beam of thermal neutrons from a neutron guide of the Garching research reactor FRM, polarized to 95%, enters a magnetic field region, precesses about a classical field during the time of passage t, and passes a second neutron polarizer for spin analysis. To simulate the Jaynes-Cummings model the fields $B_1(n)$ need not be time dependent because the rotating wave approximation allows us to go to the rotating frame [in which, in resonance, B_0 vanishes and $B_1(n)$ is stationary] without affecting $\langle \sigma_z(t) \rangle$. Furthermore, the various fields $B_1(n)$ need not be applied all simultaneously, but can be applied successively, provided the neutron counts are all added up in one single counter.

The static fields $B_1(n)$, typically of mT amplitude, were generated by a simple solenoid of diameter 9 cm, wound around the neutron beam over a length of 50 cm. The power supply regulation had to be of sufficient quality to allow the precise setting also of the very small values of the difference fields $\Delta B_1(n)$ defined below. The initial direction of neutron polarization was along the vertical z and at right angles to the common horizontal neutron beam and $B_1(n)$ field axis x. The counting time for each $B_1(n)$ was set proportional to the weight $P(n)$.

To measure collapse and revival of $\langle \sigma_z \rangle$ one needs to vary the interaction time t or, alternatively, the coupling strength g. For time-of-flight measurements the thermal "white" neutron beam of mean velocity 1300 m s^{-1} was pulsed with the aid of a mechanical chopper wheel to give 35 μs long bursts at 15 ms interval. The arrival time of the neutrons at the counter, situated 5.3 m downstream, then is proportional to the interaction time t. The neutron counts were stored in a multiscaler unit triggered by the chopper wheel. As each time-of-flight spectrum only covered a limited time interval the measurement was repeated with different settings of the overall strength g of the magnetic B_1-field values, and the data sets were joined.

The resulting time-of-flight spectrum for $\bar{n}=10$ is given in Fig. 1(a), together with a fit by (2). Our setup merely provides a Fourier transform of the discrete field spectrum shown in Fig. 2(a). But this is exactly what a quantized field would do to a particle's polarization $\langle \sigma_z \rangle$ in a spin-precession experiment, or to an atomic inversion in the one-atom maser. The spectra of Fig. 2 were derived by exact diagonalization of (1).

The complicated intertwining of the quantized fields and the particles becomes apparent only when one looks at the *transverse* polarization $\langle \sigma_y \rangle$. In Ref. [5] it was

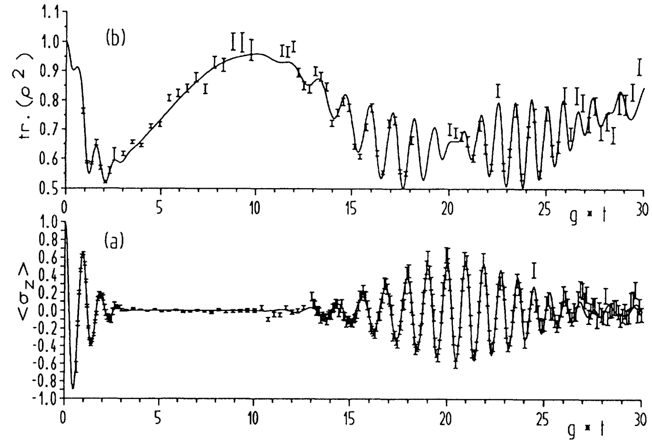

FIG. 1. (a) The response of polarization $\langle \sigma_z \rangle$ to a Glauber coherent field, displaying collapse and revivals; (b) hidden coherence in the collapse region. Bars: simulation with neutrons; lines: theoretical expectations.

pointed out that at the time when $\langle \sigma_z \rangle$ has completely collapsed an almost complete atomic coherence will have built up, visible in $\mathrm{Tr}(\rho^2)$, where ρ is the atom's density operator. This "hidden coherence" must be all due to $\langle \sigma_y \rangle$, so our second statement is as follows.

(ii) In the collapse region a transverse polarization $\langle \sigma_y \rangle$ builds up slowly, reaches a maximum of nearly 100% in the middle of the collapse region, and decays again.

At first sight this behavior is strange because (in the rotating frame) this transverse polarization $\langle \sigma_y \rangle$ is almost stationary in spite of the presence of the B_1 fields. However, this phenomenon can readily be explained by working out the system's wave function.

(iii) The transverse polarization $\langle \sigma_y \rangle$ behaves as if each particle was independently precessing about one of

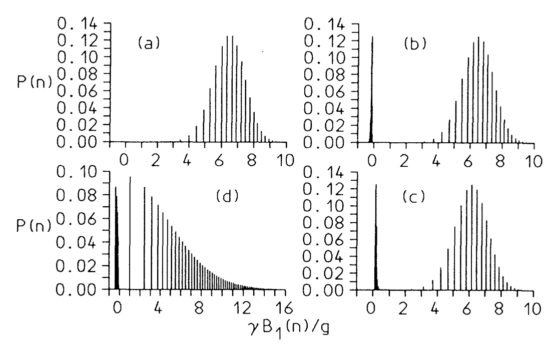

FIG. 2. Distribution of the discrete classical field values needed to simulate collapse, revivals, hidden coherence, and spontaneous polarization. (a)–(c) coherent, (d) thermal radiation. Mean photon number is $\bar{n}=10$. Distribution (a) is used for simulation of $\langle \sigma_z \rangle$, (b) and (d) for $\langle \sigma_y \rangle$, all spin up, and (c) for $\langle \sigma_y \rangle$, spin down. Note that in (b) the difference spectrum lies at positive field values, and in (c) at negative field values.

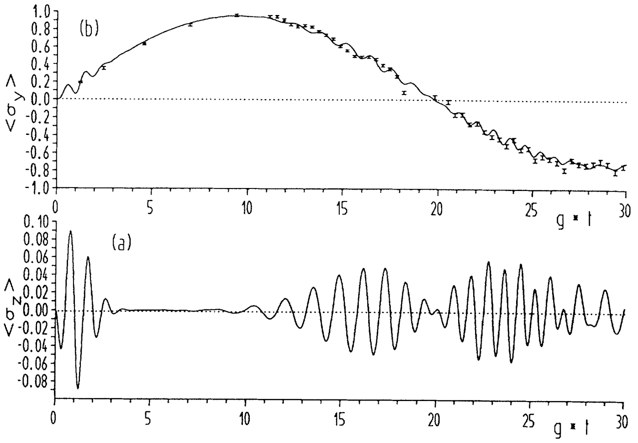

FIG. 3. Spontaneous polarization of initially unpolarized particles in a Glauber coherent field. (a) Rise of $\langle\sigma_z\rangle$, and (b) of $\langle\sigma_y\rangle$.

the mean fields $\bar{B}_1(n)=\frac{1}{2}[B_1(n)+B_1(n+1)]$, *or one of the difference fields* $\Delta B_1(n)=\frac{1}{2}[B_1(n)-B_1(n+1)]$.

Hence, the phenomenon of hidden coherence can be described as a slow beating between neighboring Rabi frequencies $\gamma B_1(n)$. We simulated this case by exposing the neutrons, initially with spin up, to the field amplitudes $\bar{B}_1(n)$ and $\Delta B_1(n)$ displayed in Fig. 2(b), while analyzing for $\langle\sigma_y\rangle$. From the measurements we constructed $\mathrm{Tr}(\rho^2)=\frac{1}{2}(1+\langle\sigma_y\rangle^2+\langle\sigma_z\rangle^2)$, shown in Fig. 1(b). It fits well to the theoretical curve of Fig. 1 in Ref. [5].

Our main interest is in the phenomenon of spontaneous polarization.

(iv) Unpolarized particles, when exposed sufficiently long to a resonant, quantized radiation field, will become highly polarized.

Of course, we cannot simulate this effect with a beam of unpolarized neutrons. So we first measured the neutron response for initial neutron spin up, then for initial neutron spin down, each with its appropriate field distribution [for instance Figs. 2(b) and 2(c)], and added the signals. In a real experiment with one single quantized field, on the other hand, each neutron spin state in the unpolarized beam would automatically only see its appropriate set of fields.

Examples of this spontaneous polarization are displayed in Figs. 3(a) and 3(b). For times much shorter than the revival time $t_R=2\pi\bar{n}^{1/2}/g$, and for photon number $\bar{n}\gg 1$, we find for the coherent field case the spontaneous polarizations $\langle\sigma_z\rangle\approx -\pi(t/t_R)\sin(\omega_1 t)$ and $\langle\sigma_y\rangle \approx 2\pi(t/t_R)\sin^2(\omega_1 t)$, with $\omega_1=2g\bar{n}^{1/2}$. In the collapse region, on the other hand, one has $\langle\sigma_y\rangle\approx\sin(\pi t/t_R)$.

The size of the magnetic field B_0 only influences the characteristic time t_R needed to reach the maximum polarization, but not its size which approaches 100% for not too small $\bar{n}$. For zero magnetic field this maximum is shifted to infinity, as it is in the "classical" limit of large photon numbers.

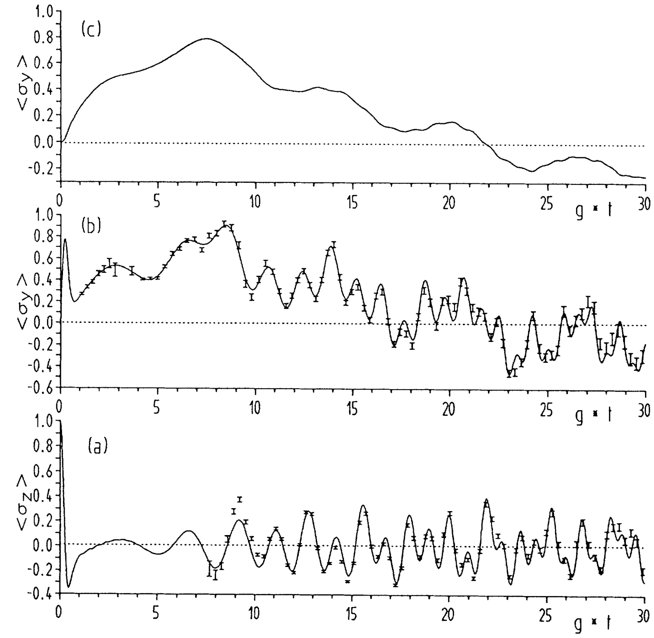

FIG. 4. Response to a thermal radiation field. (a) Collapse and no revival of $\langle\sigma_z\rangle$; (b) hidden coherence in $\langle\sigma_y\rangle$; (c) spontaneous polarization of $\langle\sigma_y\rangle$ for an initially unpolarized beam.

The photon content of the cavity may change by one photon upon the passage of a particle. But neither the short time behavior of the spontaneous polarization nor its maximum value are, for $\bar{n}\gg 1$, very sensitive to the size of $\bar{n}$.

This phenomenon of spontaneous polarization can again be understood by looking at the classical field distributions, for instance for $\langle\sigma_y\rangle$: Figure 2(c) shows the pattern needed for the beating of particles initially in the "down" state. The mean fields $\bar{B}_1(n)$ remain the same as for spin up. The difference fields $\Delta B_1(n)$, however, change sign, and therefore induce the same sign of $\langle\sigma_y\rangle$ for both initial spin directions, i.e., a large $\langle\sigma_y\rangle$ slowly appears even for zero initial polarization of the beam.

Interestingly, the same arguments hold for the interaction of particles with radiation having *thermal* photon statistics. This can readily be understood from Fig. 2(d): The difference spectrum from a field distribution exponential in n will produce a similar beating phenomenon in $\langle\sigma_y\rangle$ as for the Glauber case [Figs. 4(b) and 4(c)].

(v) The phenomenon of hidden coherence and spontaneous polarization occur also for particles interacting with thermal radiation.

This is remarkable because revivals are known to be completely suppressed in the thermal radiation case; see Fig. 4(a). This feature may also simplify the experimental detection of spontaneous polarization.

(vi) As an additional pure quantum field effect we find

an oscillation of $\langle\sigma_x\rangle$ *along the direction of* B_1.

This is an example of a spin moving into a direction which is forbidden classically.

Could some of the quantum field effects evoked in (i) to (vi) be measured in a real experiment with a beam of spin-polarized particles? For an alkali atom in a resonator of volume V one has, in SI units, $g=6.0\times10^{-4}\times(B_0/V)^{1/2}$. For $B_0=5$ T and a microresonator of 1 mm^3 volume, $g=40\ s^{-1}$. A very cold beam of atoms, after a time of passage of 250 μs, has $gt=10^{-2}$. The quality factor of the resonator and of the magnetic field homogeneity should both be of order $\omega_0 t=2\times10^8$, which is feasible (for a resonator state of the art is $Q\sim10^{10}$ [15]).

The spontaneous polarization of $\langle\sigma_z\rangle$ in Fig. 3(a) starts like $(gt)^2$ and would then give a 10^{-4} effect, for both coherent or thermal radiation. When $\bar{n}$ is chosen (for instance via the resonator temperature) such that the fast component of $\langle\sigma_y\rangle$ reaches its first maximum, see Fig. 3(b), then $\langle\sigma_y\rangle\sim(gt)^2\sim10^{-4}$ for the above example, but would need a $\pi/2$ flip for detection.

Atomic beam PNC experiments often are sensitive to effects much smaller than this. However, even if some of them [16] employed gold plated cavities, their quality factor was too low to allow quantum field effects to develop. Further, typical cavity volumes were larger, and splittings and flight times smaller than in our example.

For a neutron $g=2.0\times10^{-8}(B_0/V)^{1/2}$. In $B_0=5$ T and a resonator of 1 m length, 4 cm diameter, $g\sim10^{-6}\ s^{-1}$. After a neutron storage time of order of the neutron lifetime of $\sim10^3$ s, one has $gt\sim10^{-3}$. With ultracold neutrons the measurement of small effects is rather standard [17]. But here the quality factor needed is $\sim10^{12}$, which is rather excessive.

To conclude, spontaneous polarization effects may well be measurable in state of the art atomic beam experiments. The fact that they are induced also by thermal radiation should facilitate their detection. Existing experiments on atomic PNC violation do not have sufficiently long coherence times to suffer measurably from quantum field background effects. Polarized neutrons have served us to simulate these effects, but it would be very difficult to really measure them with neutrons.

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