# Interaction of Radiation with Matter

**C. Cohen - Tannoudji, Paris** *(First EPS Lecturer)*

**A short resume of the lecture given in London, Lund, Uppsala, Göteborg, Bucharest and Budapest by the first EPS Lecturer. It began with the premise that during the past few years, and as a consequence of the spectacular development of tunable laser sources, a great deal of experimental and theoretical activity has been devoted to various problems associated with the behaviour of atoms in intense resonant or quasi-resonant laser beams. In the lecture, some of these problems were reviewed and some simple and general ideas given to help in understanding the various phenomena which have been observed.**

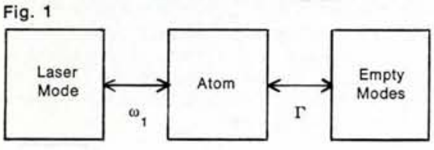
Let us consider a 2-level atom ab (atomic frequency $\omega_0$) which is irradiated by an intense single mode laser beam having a frequency $\omega_L$ close to $\omega_0$. The strength of the atom-laser coupling is characterized by the product $\omega_1$ of the laser electric field $E_L$ and the dipole moment $d$ of the transition ab; $\omega_1 = E_L d$. In the absence of damping, and for a resonant irradiation ($\omega_L = \omega_0$), the atom would oscillate between a and b at the frequency $\omega_1$, as a spin 1/2 undergoing the Rabi nutation frequency in a resonant RF field. This is why $\omega_1$ is called the Rabi frequency, even in the optical domain.

The atom is coupled not only to the laser field but also to all other modes of the electromagnetic field which are empty, and this last coupling, which is responsible for spontaneous emission, is characterized by the natural width $\Gamma$ of the upper state b (Fig. 1).

It is now possible to make a clear distinction between two extreme regimes. The intense field regime corresponds to $\omega_1 >> \Gamma$. Absorption and stimulated emission processes induced by the laser beam predominate over spontaneous emission. The atom oscillates several times between a and b before spontaneously emitting a photon. The situation is reversed in the weak field regime ($\omega_1 << \Gamma$).

Here we consider essentially the intense field regime and we use the following general theoretical method. In a first step, we ignore all damping processes (we take $\Gamma = 0$) and we determine the energy levels of the combined system "atom + quantized laser mode" interacting together, which we call "dressed states". We then introduce the damping processes which are responsible for spontaneous transitions between the dressed states.

Fig. 1




### Spectral Distribution of Resonance Fluorescence

After these general considerations, we can examine the problem which is posed by the spectral distribution of resonance fluorescence. An atomic beam is irradiated perpendicularly by a resonant laser beam and the fluorescence light (which is also observed perpendicularly to the atomic beam so that the Doppler effect is eliminated) is spectrally analyzed. At low intensities of the laser beam, one finds that the fluorescence light is monochromatic with the same frequency $\omega_L$ as the laser light (Rayleigh type scattering). At higher intensities ($\omega_1 >> \Gamma$) one gets a triplet of three lines, with a width of the order of $\Gamma$ and a splitting equal to $\omega_1$ We try here to give a simple understanding of such a "fluorescence triplet" which has been extensively studied both theoretically and experimentally by several groups across the world.

As mentioned above, we determine first the dressed states of the "atom-laser" system. To the atomic quantum numbers a, b, we must add a quantum number for the laser which is the number n of laser photons. In the absence of coupling ($\omega_1 = 0$) and at resonance ($\omega_L = \omega_0$), the unperturbed state $|a, n>$ (atom in a with n laser photons) is degenerate with $|b, n\text{-}1>$. Similarly, the two states $|a, n+1>$ and $|b, n>$ are degenerate and located at a distance $\omega_L$ above (left part of Fig. 2). Now, we introduce the atom-laser coupling. Since the atom in a, can absorb one laser photon and jump into b, the two states $|a, n>$ and $|b, n\text{-}1>$ are coupled and the matrix element of the coupling is easily found to be $\omega_1/2$. The same situation occurs for $|a, n+1>$ and $|b, n>$. It follows that the coupling removes the degeneracy and gives rise to a series of doublets of dressed states (right part of Fig. 2), with a splitting $\omega_1$, and which are just the symmetric and antisymmetric linear combinations of the corresponding unperturbed states.

Finally, the coupling with the empty modes of the electromagnetic field is responsible for spontaneous transitions between the dressed states (wavy arrows of Fig. 2). The allowed transitions connect pairs of dressed states between which the atomic dipole operator $D$ has a non zero matrix element. On gets immediately in this way the well-known triplet of three frequencies: $\omega_L + \omega_1$ (transition $|1, |2, n> \rightarrow |1, n\text{-}1>$) and $\omega_L$ (two degenerate transitions $|i, n> \rightarrow |i, n\text{-}1>$ with $i = 1, 2$).

The same approach can be easily generalized to multilevel systems and gives, for example. the possibility of studying the modifications to the Raman effect in intense laser fields.

### Photon Antibunching in Single Atom Fluorescence

We analyze now another interesting experiment dealing with resonance fluorescence in intense laser beams. Instead of looking at the spectral distribution of the fluorescence light, one measures the intensity correlations of such a light, or more precisely the distribution of the time intervals between fluorescence photons (detected by a fast photomultiplier).

A very interesting situation corresponds to the case where the atomic beam is so dilute, and the observation volume so small, that at each time, there is at most a single atom which is observed (single atom fluorescence). One predicts in this case that the probability function tends to zero as the time interval tends to zero. In other words, the fluorescence photons emitted by a single atom tend to stay away from each other. They exhibit an "antibunching" behaviour, in contradiction to the "bunching" effect

Fig. 2

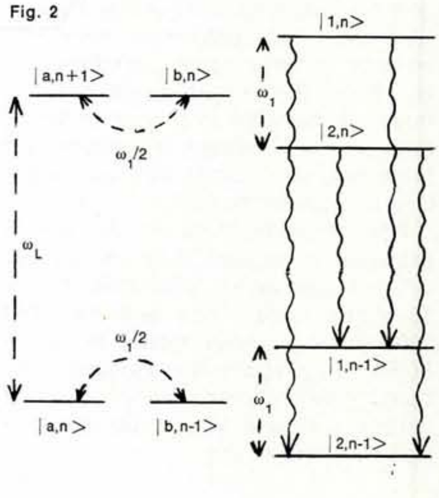
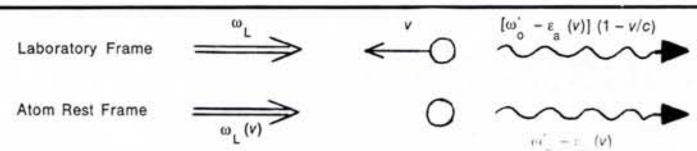


Fig. 3




discovered by Hanbury-Brown and Twiss on the light emitted by chaotic light sources.

The physical interpretation of such a result is very simple and provides a beautiful illustration of quantum-mechanical concepts. When a fluorescence photon is detected, the "wave-packet is reduced". Immediately after this detection, the atom is projected from the upper state b to the lower one a. There is a quantum jump from b to a. It follows that the atom, being in a, cannot emit another photon immediately after the first detection process. It must first be re-excited in the upper state b by the laser light and this requires a certain amount of time.

The importance of observing such an effect experimentally is due to the fact that a classical random field could never lead to an anti-bunching behaviour. Such an experiment provides therefore a direct proof of the quantum nature of the light emitted by a single atom.

**Light-Shifts**

The last problem which will be discussed deals with "light-shifts", i.e. with displacements of atomic energy levels produced by a non-resonant light irradiation.

Returning to the two unperturbed states $|a, n\rangle$ and $|b, n\text{-}1\rangle$ considered previously, if the light is non-resonant ($\omega_L - \omega_o \neq 0$), these two states are no longer degenerate but separated by an interval $\omega_o - \omega_L'$. Introducing the coupling $\omega_{1/2}$ between them, they repel each other. In a perturbative treatment (valid when $\omega_1 << |\omega_o - \omega_L|$), one finds that the light-shift $\varepsilon_a$ of $|a, n\rangle$ is equal to $\omega_1{}^2/4(\omega_L - \omega_0)$, i.e. proportional to the light intensity and inversely proportional to the detuning.

Consider an atom moving, in the laboratory frame, with a velocity $v$ towards a laser beam having a frequency $\omega_L$ close to $\omega_o$ (Fig. 3). The light-shifts induced by such a laser irradiation have to be evaluated in the atom rest frame where the laser frequency is Doppler shifted from $\omega_L$ to $\omega_L(v) = \omega_L\,(1 + v/c)$. The $v$-dependence of $\omega_L(v)$ results in a $v$-dependent detuning $\omega_L(v) - \omega_o$ between the apparent laser frequency $\omega_L(v)$ and the frequency $\omega_o$ of the transition ab. It follows that the light-shift $\varepsilon_a$ of a, which depends on this detuning, is also $v$-dependent.

Suppose now that we observe, in the same direction as the laser, the light spontaneously emitted from a third level c to a by an atom excited in c (for example by a discharge). The frequency $\omega_o'$ of the transition a-c is completely off resonance with $\omega_L$ so that level c is not perturbed by the laser. In the rest frame, the emitted frequency is equal to $\omega_o'$ corrected by the light-shift $\varepsilon_a(v)$ of a, i.e. to $\omega'_o - \varepsilon_a(v)$. Coming back to the laboratory frame introduces the well known Doppler factor $(1 - v/c)$ since the atom is moving away with a velocity $v$ (wavy arrows of Fig. 3).

Now, the basic idea to compensate Doppler broadening is to try to achieve a compensation between the $v$-dependence of the light-shifted internal frequency $\omega'_o - \varepsilon_a(v)$ and the $v$-dependence of the emission Doppler factor $(1 - v/c)$, in order to have, in the laboratory frame, *all* atoms emitting at the same frequency in the forward direction. This can be done by adjusting the frequency and the intensity of the laser light. A theoretical expression is derived for the compensation condition and experimental results obtained on $^{20}Ne$ atoms give experimental evidence for such a compensation mechanism.

The most interesting feature of this effect is its high anisotropy. If one looks at the light emitted not in the forward but in the backward direction, the Doppler emission factor changes from $(1 - v/c)$ to $(1 + v/c)$. If the Doppler broadening is compensated for one direction of emission, it is clearly doubled for the opposite one. Such a scheme could therefore provide an atomic medium emitting with the homogeneous width in one direction and with twice the Doppler width in the opposite direction.

To conclude this review of light-shifts let us note that recent atomic beam deflection experiments using transverse dipole forces may be interpreted in terms of position-dependent light-shifts. An intensity gradient of the laser beam introduces a gradient-dependent light-shift of the ground state. When the detuning $\omega_L - \omega_o$ is large enough, this appears as a potential energy for the atom, giving rise to dipole forces which can deflect an atomic beam. Moreover as the light-shift varies as $(\omega_L - \omega_o)^{-1}$ one can change the sign of the force by just changing the sign of the detuning.



**FURTHER READING**

*Frontiers in Laser Spectroscopy,* Les Houches 1975, ed. R. Balian, S. Haroche and S. Liberman (North Holland, Amsterdam) 1977.

Hanbury-Brown R. and Twiss R.Q. *Nature* 177 (1956) 27.

Proceedings of the 2nd. International Symposium on Frequency Standards, Cooper Mountain 1976, *Metrologia* **13** (1977) 161.

Cohen-Tannoudji C., Hoffbeck F. and Reynaud *S. Opt. Comm.* **27** (1978) 71.

Bjorkholm J.E., Freeman R.R., Ashkin A. and Pearson D.B. *Phys. Rev. Lett.* 41 (1978) 1361.

Reynaud S., Himbert M., Dupont-Roc J., Stroke H.H. and Cohen-Tannoudji C. *Phys. Rev. Lett.* **42** (1979) 756.