

**LETTER TO THE EDITOR****Correspondence of classical and quantum irreversibilities**

Jacques Moret-Bailly†

Laboratoire de physique, Université de Bourgogne, BP 400, F21011 Dijon Cedex, France

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**Abstract.** The reversibility of classical mechanics is broken by the Carnot principle; in quantum mechanics, the time inversion invariance is broken by the principle of state decoherence. In both cases, a greater complexity produces a faster irreversibility. These principles are applied to problems related to absorption and diffusion of light. It appears that Raman scattering in extremely low-pressure gases shifts the frequency of the incident light, is space coherent and thus may be confused with the Doppler effect: the Raman scattering produces at least a part of the galactic redshift; the expansion of the universe is reduced or possibly cancelled.

Following the original hypothesis of the Copenhagen school, Schrödinger's cat would be both dead and alive up to its observation. To solve this paradox, a spontaneous 'decorrelation of coherent states' was introduced explicitly for complicated-enough systems. This complication is required for the irreversibility of a classical frictionless mechanical system, so that it seems like a thermodynamic property. We cannot compute the times of decorrelations of coherent states by quantum mechanics; thus, we shall use the correspondences with the classical problems to derive these times. Three examples, in the field of interaction of light with identical gaseous molecules (or atoms) will be given.

*Absorption of a photon by a set of molecules*

Quantum decoherence is responsible for the transition from a quantum to a quasi-classical state. It may be introduced in an interpretation of the photoelectric effect, which is at the roots of quantum theory.

Since Einstein's explanation of the photoelectric effect, it seems that a single photon interacts with a single molecule. However, a single photon is refracted by a prism, that is by a whole set of molecules. The ostensible discrepancy is a consequence of a decorrelation of states: at the beginning of an absorption, exactly as for refraction, all molecules are equivalent; thus, if we try to split the state of the system into products of elementary states, the best representation of each elementary state will be the state of a molecule bound to a fraction of the photon; these elementary states are all obtained by the same computations, so that they are coherent. The system evolves very quickly, the decoherence appears, all molecules except one return to their initial state.

In classical mechanics, a molecule is considered as a nonlinear system which permanently exchanges energy with the zero-point electromagnetic field introduced by Planck [1] and Nernst [2]. Following Poincaré's mechanics of nonlinear systems, the

† E-mail address: jmb@jupiter.u-bourgogne.fr

molecule possesses attractors which may be identified with the states of quantum mechanics. An excess of electromagnetic energy moves the molecules away from their attractors. If the system of molecules bound by the electromagnetic field were linear, the initial equipartition of the energy would remain; but it is nonlinear and a catastrophic evolution concentrates the energy of transition from an attractor to another into a single molecule [3]. The computation of the energies of the attractors is phenomenological, generally it uses Lie algebra theory, and, thus, is identical to the computation of quantum states; this phenomenology justifies the use, in molecular spectroscopy, of marginal theories, such as Padé's approximants. A classical computation of the time constant of the decoherence requires a nonlinear modelling of the dipole moments which can be done, for example, by quadratic functions which keep zero values on the attractors.

#### *Raman scattering*

The decorrelation of the coherent states was probably introduced first, implicitly, in the computation of ordinary Raman scattering: the semiclassical computation of the field scattered by all atoms on a wave surface is exactly the same, so that these fields should interfere and produce coherent Raman scattering; to obtain the observed incoherence older books [4] introduce the decorrelation without an explanation through a stochastic phase factor in the off-diagonal elements of the density matrix (not in the diagonal elements, as required to obtain the refraction!). On the other hand, if the incident light is powerful enough, or if it is made up of very short pulses, the Raman scattering is coherent; quantum theory neither indicates in which case the scattering is coherent or not, nor finds the conditions of decoherence.

In particular, in a review paper by Lamb [5] the time of decoherence was considered, without precise explanations, as the shortest molecular relaxation time. This classical evaluation is not precise enough because in spite of relaxations the refraction is a coherent scattering.

In the ground state of the molecules of a dilute gas, with low-level illumination, the relaxations are collisional. Suppose that a pulse of light illuminates the gas, and consider molecules on the same wave surface; suppose that these molecules possess a low-frequency oscillator so that the scattered light contains the incident frequency and slightly different Stokes and anti-Stokes frequencies. At the beginning of the pulse, according to Fourier theory, the three frequencies cannot be distinguished and the differences of phase of the radiated fields with the incident wave is  $\pi/2$ . The wave scattered at the incident frequency keeps this difference of phase and produces the refraction. The phase of another scattered wave changes linearly and slowly, in the same way for all molecules: the scattered light is coherent in space, that is, the wave surface of the scattered light is identical to the wave surface of the incident light. However, if collisions de-excite the molecules during the light pulse, they restart at various times, radiating with a difference of phase  $\pi/2$  with the incident light; if the molecules have large changes of phase between two collisions they finally have stochastic phases: the scattered light is incoherent.

If the time between two collisions is longer than 100 ns, ordinary monochromatic light (with a coherence duration of the order of 30 ns) may be considered as made up of short pulses, and the Raman scattering by the gas is coherent, but the gas pressure is so low that the scattered light cannot be observed in a laboratory.

#### *Coherence and decoherence of photons*

Consider the interference of two pulses of 'monochromatic' light of different frequency. If the length of the pulse is larger than the period of the beats between the sources, according

to Rayleigh's criterion, a spectrometer is able to separate the two lines. Suppose now that we reduce the length of the pulse; a spectrometer becomes unable to separate the two wavelengths, but the wave, within the pulse, is not exactly a sine wave†. Is it possible, however, to consider with sufficient precision the sum of the two waves is a sine wave during the pulse? If it is possible, the states of the two corresponding photons will be coherent, if the pulse becomes too long, we get a decoherence of the photon states.

Within the pulse, the two fields, of different amplitudes are written as

$$E \cos(2\pi \nu t) \quad \text{and} \quad Ea \cos(2\pi \mu t) \quad (1)$$

the sum of these two fields is

$$\begin{aligned} D &= E \cos(2\pi \nu t) + Ea \cos(2\pi \mu t) \\ &= E \cos(2\pi \nu t) + Ea(\cos(2\pi \nu t) \cos(2\pi(\mu - \nu)t) - \sin(2\pi \nu t) \sin(2\pi(\mu - \nu)t)). \end{aligned} \quad (2)$$

Suppose that the difference of frequencies and the amplitude of one of the fields are low enough to consider that  $a$  and  $\mu - \nu$  are first-order small quantities; we may develop the corresponding trigonometric functions:

$$\begin{aligned} D \sim E \cos(2\pi \nu t)(1 + a) - 2Ea\pi(\mu - \nu)t \sin(2\pi \nu t) - 2Ea(\pi(\mu - \nu)t)^2 \cos(2\pi \nu t) \\ + \frac{4}{3}Ea(\pi(\mu - \nu)t)^3 \sin(2\pi \nu t) \end{aligned} \quad (3)$$

set

$$\tan(\phi t) = 2a\pi(\mu - \nu)t/(1 + a) \quad (-\pi/2 < \phi \leq \pi/2) \quad (4)$$

where  $\phi$  is a first-order quantity.

$$\begin{aligned} D \sim E(1 + a)((\cos(2\pi \nu t) \cos(\phi t) - \sin(2\pi \nu t) \sin(\phi t))/\cos(\phi t) \\ - 2Ea(\pi(\mu - \nu)t)^2 \cos(2\pi \nu t) + \frac{4}{3}Ea(\pi(\mu - \nu)t)^3 \sin(2\pi \nu t)). \end{aligned} \quad (5)$$

In a second-order approximation, the second line may be neglected so that we get a sine wave within the pulse; this is even true if  $2\pi(\mu - \nu)t$  is only small enough to develop the trigonometric functions. In a first-order approximation,

$$D \sim E \cos((2\pi \nu + \phi)t). \quad (6)$$

The waves interfere into a single wave within the pulse, that is, the corresponding photons have not undergone decoherence yet.

At longer times, the coherence of the scattered light disappears, this light must be studied alone and multiple scatterings produce the completely incoherent usual Raman scattering.

#### *Application to the Raman effect in space*

As the pressure is low in space, collisions are rare and the Raman effect is space coherent; thus, the frequencies of the images are changed without loss of sharpness of the images (except that the diffraction may be larger at longer wavelengths).

The amplitude scattered by a volume much larger than the cube of the wavelength is very small, so that the coefficient  $a$  of equation (1) is very small; if the Raman frequency  $\nu - \mu$  is not too large, the scattered photons are coherent with the incident one, so that we get a shift of the line in place of the emergence of satellite lines.

Successive scatterings add their shifts. What would be the density of active molecules, such as  $H^{3+}$ , needed to produce the entire shift usually assigned to the expansion of the

† Rayleigh's criterion is broken in another field: photoelectric measurements allow interferometers to control optical surfaces with a precision much better than a wavelength. Our problem is slightly different because the two interfering beams have different frequencies.

universe? To avoid a complicated spectroscopic study, and to get only an order of magnitude estimate, consider a model molecule which possesses two low-level states 1 and 2, with the same properties (symmetries, dipole moments, etc) and a very high level; suppose that the difference of the energies of the low levels  $w = hf$  is small and that their distance  $hF$  to the high level is large. The ratio of the populations, a Boltzmann factor, may be developed so that the difference of populations  $N_1 - N_2$  is proportional to  $w/kT$ . Set  $A$  as the fraction of the diffused amplitude by any of the four two-photon transitions, for a thickness  $L$ , and the incident frequency  $\nu$ .  $L$  is not too large, so that  $A$  is small, in other words, a single photon is produced by the interaction of matter with a large number of coherent incident photons. The refractive index is

$$n = 1 + 2cA/(2\pi\nu L). \quad (7)$$

The proportion of atoms  $N_1/(N_2 + N_1)$  produces anti-Stokes radiation partially compensated by the fraction of atoms  $N_2/(N_2 + N_1)$ . The efficiently scattered relative amplitude  $A(N_1 - N_2)/(N_2 + N_1) = Aw/2kT$  is a coefficient of reduction of the frequency shift  $w/h$ ; thus, the absolute frequency shift is

$$\Delta\nu = -Aw^2/(2hkT) = -\pi\nu L(n - 1)w^2/(2chkT). \quad (8)$$

If the dispersion is not too large,  $\Delta\nu$  is proportional to  $\nu$ , so that the effect may be confused with a Doppler shift.

If a redshift is not too large, by Hubble's law

$$\frac{\Delta\nu}{\nu L} = \frac{1}{L} \sqrt{\frac{c - LH_0}{c + LH_0}} - \frac{1}{L} \approx -\frac{H_0}{c}. \quad (9)$$

Using (8), (9) and the dispersion formula

$$n - 1 \approx \frac{2kTH_0}{\pi hf^2} \approx \frac{Ne^2}{8\pi^2 m \epsilon_0 F^2} \quad (10)$$

where  $e$  and  $m$  are the charge and the mass of an electron.

The number of scattering molecules per cubic metre must be

$$N \approx \frac{16\pi\epsilon_0 mk}{he^2} \left(\frac{F}{f}\right)^2 H_0 T = 3.3 \times 10^8 \left(\frac{F}{f}\right)^2 H_0 T. \quad (11)$$

For a Hubble constant of  $2.5 \times 10^{-18}$ , an intergalactic temperature  $T = 2.7$  K, and an average ratio  $F/f = 10^5$ ,  $N = 22$  molecules/m<sup>3</sup>.

The energy lost by the light pumps the molecules which may produce spontaneously or amplify the isotropic 2.7 K radiation discovered by Le Roux [6].

### Conclusion

The correspondence between classical and quantum theories verifies that the decoherence of quantum states is related to interactions in systems where the number of particles is large. But the quantum decoherence corresponds to very different classical effects, here relaxations, collisions and interference of short pulses.

A notable minority of astrophysicists think that the Doppler effect cannot explain all observed redshifts [7, 8], but they were unable to find an alternative physical effect because usual studies of optics consider time-coherent waves: considering that a wavelength is a unit of length, a lineshift with the condition of space and time coherence can only be produced by a Doppler effect. We have described a possible alternative which also produces low-energy radiation; the effect exists and astrophysicists can establish whether it is important or not.

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