How empty is the vacuum?

A solution to the problem of radiation from an atom in a loss-free cavity raises questions about the reality of emptiness.

WHAT happens when an atom in an excited state is allowed to radiate not in a vacuum (the simple case) but in a conducting metallic cavity of some kind, a waveguide for example? On the face of things, this seems the kind of problem that would have been tackled on the back of an envelope by any one of Bohr, Born or Heisenberg more than half a century ago. It is therefore something of a surprise that a group from the University of Rochester in the United States now claims to have made "the first fully quantum mechanical predictions about the spectrum of spontaneous emission into a lossless cavity" (J.J. Sanchez-Mondragon, N.B. Narozhny and J.H. Eberly, *Phys. Rev. Lett.* **51**, 550-553; 1983).

Quite apart from the inherent (and surprising) outcome of the calculation, the paper adequately explains why the problem has not been solved before and may even help to clear up a general confusion about the sense in which empty space is supposed to be filled with "virtual photons" and, for that matter, "virtual gluons", "virtual gravitons" and even the occasional (and "virtual") Z^0 or $W^\pm$ meson. For Sanchez-Mondragon *et al.* show that the radiation from a single isolated atom in a lossless cavity may be profoundly different from that of a similar atom in free space, which is, after all, only another way of saying that the two regions of vacuum, each of them empty, are nevertheless differently constituted.

The problem has an obvious practical interest in the operation of masers, and the earliest study quoted by Sanchez-Mondragon *et al.* is credited to E.M. Purcell in 1946; understandably that was concerned with the properties of radiation from "atoms" (for examples ammonia molecules) in cavities tuned to the characteristic radiation frequency. Interest in what happens far away from resonance was, however, stimulated two years ago by Daniel Kleppner (*Phys. Rev. Lett.* **47**, 233-236; 1981) who argued that an atom whose characteristic radiation frequency is very different from that of the cavity containing it should have an abnormally sharp linewidth and therefore a much longer lifetime against spontaneous radiation than a similar atom in free space. Obviously atoms in such a state would have many practical uses, perhaps in still further improvements of precision frequency standards. But merely checking that linewidths would be narrowed might help to clarify

what is meant by the physical nature of vacuum fields.

That the vacuum of free space should differ in some way from that inside a conducting cavity is natural enough. Classically or otherwise, a cavity will not without difficulty sustain radiation whose wavelength is greater than its own dimensions. In linear waveguides there is always a cut-off frequency ν_0 such that radiation of lower frequency will not propagate efficiently. If microwaves of longer wavelength do embark along such a waveguide, their energy will quickly be dissipated as ohmic heating in the walls. So much is amply confirmed by everyday experience, but what then will happen if an atom in an excited state with a characteristic frequency below this cut-off is placed in such a waveguide, supposed empty of everything else? The problem is essentially one of quantum mechanics and the result, in the ideal case, is that even if the atom were in an excited state, it could not get rid of its energy by radiation.

This simple (but ideal) conclusion naturally fits well with the picture of radiation processes developed in the past half-century. The system of an isolated atom in an otherwise empty cavity consists of three parts — the atom, the walls of the cavity, and the radiation field of the intervening vacuum with which each of the other components interacts. A photon, being the quantum equivalent of a plane wave or its equivalent, cannot therefore exist if its energy is less than half of the cut-off frequency. But the atom is coupled with the radiation in such a way that the de-excitation of an excited atom is accompanied by the creation of a photon with the same energy in the radiation field. But since the photon cannot exist, the atom cannot radiate.

In reality, as Sanchez-Mondragon *et al.* show, the problem is more complicated. First, it is far from clear what is meant by the spectrum of the radiation that would be generated in these circumstances, for the radiation of a single photon by an atom is not a stationary process, and they are forced to calculate the probability that photons with frequencies in some finite range will be generated. A further difficulty is that approximate solutions will not suffice, and that the shape of the spectrum is likely to differ from that arising with radiation in free space. All this is enough to explain why the problem was not solved in 1925.

The solution now published deals with an atom at the centre of a spherical cavity, and confirms Kleppner's semi-quantitative predictions. In particular, for atoms with characteristic frequencies below the cut-off of the cavity, the spectral lines are narrower than in free space, which entails that the lifetime of the atom is increased. And conversely, if the radiation frequency should be near one of the characteristic resonance frequencies of the cavity, spectral lines will be broadened (or lifetimes decreased).

The surprise, however, is that the calculations show that near resonance (or coincidence of the frequency of atomic radiation with that of a stationary radiation mode within the cavity), the single broadened spectral line splits into two. And if account is taken of the presence within the cavity of pre-existing radiation, the broadened hump of the spectral line is marked by three peaks not symmetrically disposed in frequency. The first splitting into two of the broadened emission line is consistent with quantum electrodynamics. The second, in a cavity not empty of radiation at the outset, is new.

Telling the physical significance of this result will be far from straightforward. The "atoms" considered by Sanchez-Mondragon *et al.* are simple structures, supposed to have only one possible transition frequency so as to avoid the complications of competing radiation processes. So much is fair. But discussion is likely to centre on the mathematical process used for simulating the observation of the spectrum of the radiation from a single atom emitting a single photon into the vacuum within a cavity. The question will be whether Sanchez-Mondragon *et al.* have assumed possible more accurate measurement of the phase associated with a photon than quantum mechanics allows. They promise a later account of the appearance of the third peak in the radiation in terms of phase coherence between the radiating atom and the cavity.

Whatever the outcome of the theoretical argument, the phenomenon should be measurable. Two years ago, Kleppner estimated that it should be possible to detect line-narrowing below a waveguide cut-off frequency by using a 0.4 cm diameter waveguide and, as radiative transitions, those of the Rydberg series of hydrogen-like atoms. Subsequently (see *Nature* **295**, 192; 1982) the effect was measured in the laboratory by Kleppner and colleagues.

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