asteroids graze the sun or escape from the solar system, rather than evolve as near-Earth asteroids. Gladman *et al.* (*8*) generalized that discovery: Only a small fraction can be removed by Earth or Mars encounters. In other words, those strongest resonances, originally thought to be the best candidates for delivering meteorites, are too strong to provide efficient routes. Moreover, evolution after bodies become planet crossers proved to be governed by chaotic resonance effects.

Now, Migliorini *et al.* (*1*) report that numerous weak resonances and interactions among the resonances cause chaotic behavior capable of raising main-belt eccentricities to Mars crossing. Objects then break away from the resonances when they have close encounters with Mars and subsequently evolve as Mars crossers, until they become near-Earth asteroids. That subsequent evolution is speeded by a series of minor resonances that yield fairly chaotic evolution, lasting a few times 10^7 years, during which a reasonable fraction is likely to hit Earth. Thus, in broad terms, the classical hypothesis seems to be restored and placed on a firm computational footing: Several resonances provide the escape route from the main belt and allow bodies to reach Earth in a few tens of million years.

Another potentially important mechanism is the Yarkovsky effect, in which thermal radiation from a small rotating asteroid causes drift in its distance from the sun. Meteorite-sized main-belt bodies may be preferentially swept into resonances, compensating for the inefficiency of delivery from the strongest resonances (*9*).

An international community of researchers is currently integrating our expanded knowledge of delivery processes, meteoritic physical properties, arrival trajectories, asteroidal characteristics, and collisional processes into comprehensive models of the formation and transport of meteorites and other near-Earth asteroids. Although the new results regarding orbital evolution include important details and evolutionary processes that had not been anticipated, the process is similar in many fundamental ways to what had been widely assumed in the past. If progress continues at the present pace, fundamental questions may be answered before long.

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PERSPECTIVES: QUANTUM OPTICS

Quantum Control of the Inevitable

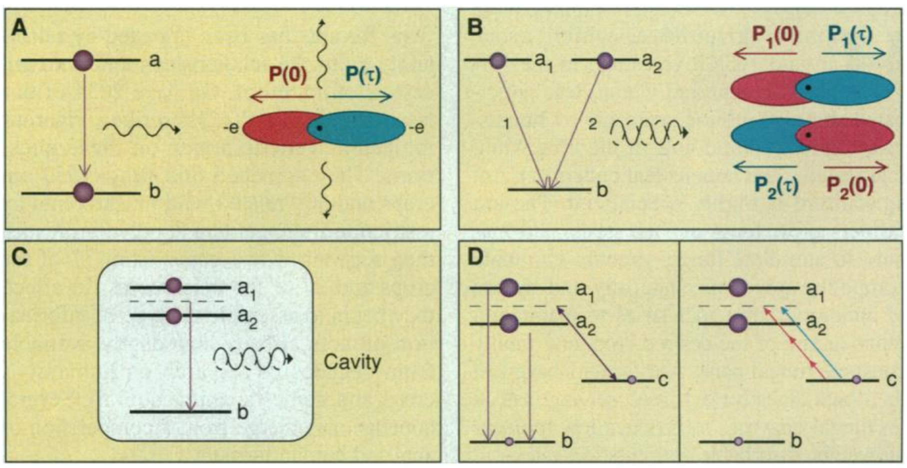
Marlan O. Scully and Shi-Yao Zhu

After 100 years of intensive study, we are still regularly discovering intriguing new insights and effects in quantum mechanics. For example, early in the development of quantum theory, we learned from Max Planck and Niels Bohr that atoms and molecules can "live" only in certain energy levels and not in between. But what if we prepare our atoms to have, on average, half of the energy of the first excited state? In such a case, the atoms are said to be in a coherent superposition, in which every atom is half in the ground and half in the first excited state (not half of the atoms in the ground and half of them in the excited state).

This "coherent control" has led to many interesting and counterintuitive effects (*1*) over the past decade, among them the electromagnetically induced transparency of Harris and co-workers (*2*), lasing without inversion (*3*, *4*), nonlinear optics without phase matching (*2*), and even suppression of atomic decay by spontaneous emission (*5*).

Concerning the latter, we note that the decay of optically excited atomic and molecular states is an inevitable fact of life. Knock atoms to an excited state, and they will tumble back to the ground state through spontaneously emitted light. In recent studies, however, a new and somewhat subtle technique has been developed that suppresses decay from a multilevel atom by means of quantum interference effects induced by coherent laser radiation. This is summarized in the figure, where it is shown that an excited state will decay until a coherent field is applied that "shuts off" the spontaneous emission. In the words of Paul Berman (*6*): "This is a rather remarkable result, since one might imagine that, owing to the short correlation time of the vacuum field, such modification of spontaneous emission would be strictly forbidden."

Consider the case of an optically excited atom as depicted in panel A of the figure. There we see that the electron charge cloud associates with an atom in a superposition of ground state (b) and excited state (a), which oscillates in time and radiates light as a tiny dipole antenna. The emitted light carries off energy and, to conserve energy, the atom drops to the ground state (*7*).



Coherent darkness. **(A)** The atom in superposition of a and b states has electric dipole pointing to the left at time $t = 0$ (red) and to the right at $t = \tau$ = half cycle later (blue). The black dot represents the atomic nucleus. **(B)** Two levels at the same energy prepared out of phase do not radiate. **(C)** The atom placed in electromagnetic cavity tuned to a frequency midway between levels a_1 and a_2 will not radiate if the states are coherently prepared. **(D)** (Left) Four-level atom with driven transition from level c to a point between a_1 and a_2 can also lead to cancellation of spontaneous emission. (Right) Same situation, but now the transition from c takes place through two paths and provides additional flexibility.

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But suppose our atom has a pair of excited states as in panel B. There it is seen that the excited states a_1 and a_2 couple with the ground state b, yielding two dipole currents, one associated with the $a_1 \leftrightarrow b$ transition (antenna 1) and one with the $a_2 \leftrightarrow b$ transition (antenna 2). Excited individually, both states a_1 and a_2 decay as their atomic currents radiate energy. However, when the atomic radiators 1 and 2 have the same frequencies (as is the case when states a_1 and a_2 have the same energies) and the atomic currents 1 and 2 are 180° out of phase, then the emitted radiation fields cancel. Thus, the atom remains excited because the electromagnetic field carries away no energy. In other words, the currents in antennas 1 and 2 cancel, and the atom is "locked" in the superposition of equal energy states a_1 and a_2 (*8*).

But now the plot thickens. Under some conditions, even when the energies of the a_1 and a_2 states are not equal (and the dipole currents 1 and 2 have different frequencies), the atom can still be locked in an excited state a_1, a_2 doublet. For example, we found some time ago (*4*) that when an atom is properly prepared and placed in a cavity as in panel C, it can be locked in an excited state doublet. This example is a harbinger of the present studies. We now know that even in free space, the driven atom of panel D can yield two dipole currents having the same frequency and oscillating 180° out of phase. For example, when the a_1, a_2 pair is driven by a laser coupling the pair to another state (c), as on the right side of panel D, we find antennas 1 and 2 can oscillate at the same frequency.

The interesting point is that the antennas 1 and 2 corresponding to the $a_1 \leftrightarrow b$ and $a_2 \leftrightarrow b$ transitions can oscillate at the same frequency when levels a_1 and a_2 are coherently coupled or driven to some fourth level (c in panel D). Even if we inject the atom in state a_1 only, the laser field will force the atom (partially) into an "anti–phased-antenna" configuration and the atom will remain (partially) excited.

An experiment was carried out in molecular sodium (*9*), which supports the theoretical predictions. Furthermore, recent work of Paspalakis and Knight (*10*) has shown that it is possible to use two driving fields to quench spontaneous emission. The advantage of the two-field approach is that it allows us to control spontaneous emission by changing the relative phase between the two fields. Further work (*11*) has shown that it is possible to view the problem from the perspective of a special dressed state prepared by the laser and resulting in states a_1 and a_2 acquiring equal energy components.

This quenching of spontaneous emission by quantum coherence provides yet another example of counterintuitive quantum effects. Might there be further surprises in store? Probably. Zhou and Swain (*12*), have shown that the present ideas can sharpen spectral lines and is potentially of interest as a spectroscopic tool. Looking further ahead, we might ask if we can hope to enhance lifetimes in complex molecules? Perhaps, time will tell.

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PERSPECTIVES: EVOLUTION

Ants, Crops, and History

Jared Diamond

Human agriculture, which arose around 10,000 years ago in the Fertile Crescent and China, was anticipated about 50 million years ago by fungus-growing New World ants of the tribe Attini that includes the famous leaf cutters (*1*). Ant agriculture is highly specialized. The ant farmers grow fungi in their nests, add manure to stimulate fungal growth, eliminate competing weeds mechanically and by use of antibiotic herbicides so as to maintain a monoculture of the desired crop, and finally consume fungal parts. Ant farmers have lost their own digestive enzymes, relying instead on fungal enzymes to produce low molecular weight absorbable nutrients.

Ant agriculture raises many unsolved questions, with obvious parallels to human agriculture. But progress on these questions for ants has been impeded by uncertainty as to the relationships and wild ancestors of ant crops. On page 2034 of this issue, Mueller *et al.* (*2*) describe a vigorous molecular genetic attack on these questions. They screened 862 fungi (553 ant crops and 309 related wild mushrooms) by restriction fragment length polymorphisms, then sequenced two genes from 57 of the crops and 27 of the mushrooms. In effect, they begin to assemble the type of information on ants already abundantly available from decades of research on humanity's crops and domestic animals (*3–5*). Several conclusions emerge from a comparision of ants and human farmers.

All ant farmers propagate their fungal crops vegetatively (asexually) as clones. Humans do so for some crops, such as bananas, but most of our crops and all livestock (until Dolly) are grown by sexual reproduction from seeds or pregnancies. Moreover, any given ant "village" (nest) cultivates only a single crop (fungal clone), which nevertheless supplies much or most of the ants' nutrition. In contrast, most human farming villages cultivate many different crops; those that cultivate monocultures rely on trade to obtain other cultivars for nutritional balance. The closest human parallels to ant monocultivators are some Old World arid-environment herders heavily reliant on a single domestic animal (horse or camel) without crops.

Molecular evidence indicates at least five clades of ant fungi, attesting to at least five independent domestication events, rather than the single event previously thought possible. Almost all of those fungal crops belong to a single tribe of fungi, the Leucocoprini. Human herds are only slightly more diverse: only 14 significant species of large mammalian domestic herbivores worldwide, and originally only one species in the Americas, six in East Asia, and seven in West Eurasia (*6*). But human farmers have domesticated hundreds of crops belonging to very different groups, ranging from cereals and legumes to root crops and nut trees.

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