Interview: Dr. George C. Baldwin

Needed: a broad research program

This interview was given to Charles B. Stevens by Dr. George C. Baldwin of Los Alamos National Laboratory in July of this year.

Q: You have been involved in the gamma-ray laser, or what is called the graser, for some period of time.
Baldwin: That's right. We first took a look at this in early 1961, as did a number of other groups at about that same time. It was rather obvious then, with the Mössbauer effect, and the existence of lasers that covered the range from the microwaves through the visible, that we could go into the gamma-ray region by extending the same principles. But we didn't make much progress then.

Q: What's the difference between these other types of lasers that we now see and the graser?
Baldwin: The differences are quite pronounced. There's very little in common between, for example, an ammonia maser and a ruby laser, or a big laser fusion train, or the gas laser. They're all quite different, as far as physical construction goes. However, they operate on a common principle; that is, stimulated emission, known theoretically ever since Einstein pointed it out in 1917. All of these different devices use quite different physical arrangements to achieve stimulated emission.

Q: Is the gamma-ray laser much different from these other types of lasers?
Baldwin: It would be an entirely different device, because, first of all, while all of the other stimulated emission devices use either molecular or atomic systems as the system that radiates, the gamma-ray laser would use a nuclear transition. Nuclear transitions have some unique properties, which bring some problems that other systems don't have. The major problems are the much higher energy of the transition, which means shorter wavelengths, and also the long lifetime of the transitions, which means that, although you can store energy over long periods of time, it will be difficult to release it rapidly.

Q: Are you talking about coherent nuclear energy?
Baldwin: I am talking about using the stimulated emission process to enable one to get coherent emission from a large number of nuclei, rather than the usual incoherent spontaneous emission where each nucleus radiates independently of all the others. The essence of any stimulated emission device is simply to get a large number of atomic, molecular, or, in this case, nuclear systems to radiate in synchronism. The radiation that they produce thus has a common phase, and it's the common phase and the extreme purity waves—spectral purity—that makes it possible to have the large number of applications of lasers.

Q: Could you tell us something about some of the other groups working on gamma-ray lasers, for example, in the Soviet Union?
Baldwin: I used to be in pretty close touch with people there; in particular, as you may know, there have been two joint publications I've had with Russian co-authors. In 1975 we had a paper with Rem Khokhlov, who died a few years after that. I've had a very good working relationship with Vitalii Golidanski of the Institute of Chemical Physics, and we published a review article in 1981. He has published articles separately on gamma-ray lasers.

For some reason that you and I can only speculate about, I've had no correspondence from anyone in Russia about their work for the past two years. I know that they are still working on the subject, because I still see papers appearing. There's one in the *Soviet Journal of Quantum Electronics,* an article that was published in, I guess, their November or December issue, that looked at exactly the same problem that I'm looking at right now.

So they're right up there, maybe a little bit ahead of us as far as conceptual work is concerned. As for what they're doing experimentally, I have no idea. In this country in the past year, I guess, largely because there's some hope of an SDI application (which, of course, I'm open-minded about), there have been some others interested. Carl Collins at the University of Texas at Dallas has a program, but I think he's overselling it because it neglects certain critical areas, especially the areas of crystal optics. It's a brute force approach and I think one has to be very subtle in this thing, that brute force methods just won't work. But I wish him well, and I hope he succeeds in what he is trying to do. Perhaps he may be right, I don't know, but it's not the route that I would take.

There are a number of other places where people are interested in specific aspects of the problem, now that we've begun to define them pretty well. The group at Rochester University, the Laboratory for Laser Energetics, is interested in what they can do in this field. There's a nuclear physics group there at the same university under Harry Gove, that is working hard looking for nuclear candidates, or at least he is proposing to do this. He has some very good facilities for that purpose.

Q: I believe the scientists in the People's Republic of China had published proposals some years ago on an accelerator-pumped laser.
Baldwin: That's an entirely different idea. That's not a gam-

ma-ray laser. But you are quite right. In fact, that was something I took a look at when one of our heavy-ion nuclear physics people came to me and asked, "Why can't you make an x-ray laser by pumping ions with a laser, using the Doppler effect, pumping a beam of heavy ions that are in a storage ring?" We worked it out and published it, and someone said, "I've seen that idea somewhere before!" Sure enough! It turned up in the first issue of *Chinese Physics*! They had done almost the identical system!

That shows how, if an idea has any merit at all, a lot of people are going to stumble on it independently. But we haven't pursued that further, and, to my knowledge, no one else has. I think someone should be looking at it. There are lots of approaches of course, besides this Mössbauer one that I'm involved in. It is so demanding of one's time and money, because of the many facets of science and technology involved, that I don't have time really to look at any of these others.

Q: The Fusion Energy Foundation has completed a study indicating that the gamma-ray laser or graser may indeed be what defines technology for the next century or more.
Baldwin: I wouldn't go quite that far. I've tried to be rather modest about this. Our program has been very objective and honest. We haven't minimized the difficulties at all; we've said, rather, let us identify them and bring them out into the open, let's find out what we have to do.

The fact is that we would hope for coherence lengths of meters rather than microns (which the x-ray laser people now are happy to have). Once you have generated such short wavelengths, and stored energy at such high concentration, there are going to be many, many applications. But what they will be, I've consistently declined to speculate about. I'm sure they're there waiting for us.

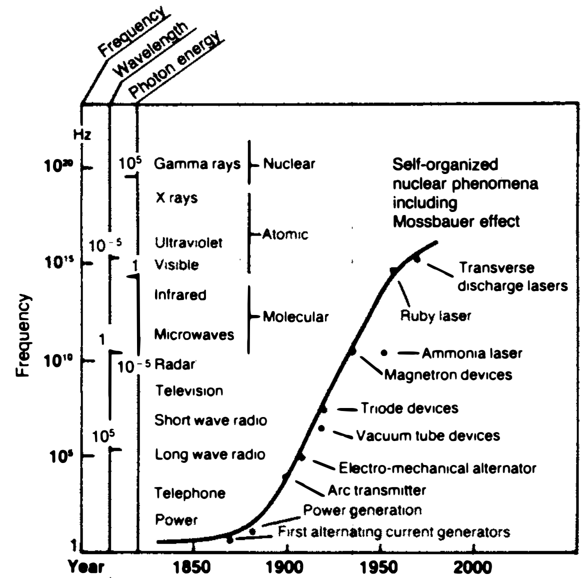
Most of the applications that optical lasers have today—nobody knew what they would be when lasers first appeared on the scene. Many of them, I think, would have been dismissed as utterly fantastic at the time—things like eye surgery, holography, nuclear fusion, any of those applications would have seemed so remote in 1955! In comparison, we're somewhere back where the laser people were in the 1950s.

Q: It does appear that gamma-ray lasers would open up the prospects for doing much finer spectroscopy of nuclear states.
Baldwin: Exactly. The same sort of breakthroughs that have taken place in the understanding of the atom, I think could occur in nuclear physics. Instead of going to higher and higher energies, I think there's a great deal to be learned by just working in the lower energy region with nuclei in their normal states rather than in the extremely abnormal conditions that exist in accelerators. The nonlinear effects that have made atomic physics such a rich field, which the laser opened up, are going to be there in nuclear physics as well, I am sure.

Q: What do you think now is probably the best approach to constructing a gamma-ray laser?
Baldwin: That has changed over the years. Originally we thought the same as everyone did back in the 1960s, that nuclear transitions with very long lifetimes could be easily pumped by radiochemical processes and then made to lase. Finally we discovered that could not be done. Although there were some ingenious ideas proposed in Russia during the 1970s, to get around what seemed to be the problem that prevented those long-lived transitions from lasing, the kinetics of the process is such that there would be no way that you could induce lasing before you had lost the population inversion—however pure you had prepared it. So, long-lived transitions are out.

On the other hand, there were proposals to use short-lived transitions, that we know from the Mössbauer effect would lase if they could be pumped. But there is no way that we can

FIGURE 1.
The electromagnetic spectrum



The points along the historical axis of the graph show the dates of the first development of devices for generating coherent electromagnetic (EM) radiation in the ranges shown on the vertical axes to the left. The three vertical axes (going from left to right) are: 1) the frequency of electromagnetic radiation in cycles per second (Hertz-Hz); 2) the corresponding wavelengths in centimeters; and 3) the energy of the quantum of action (photon) associated with a particular wavelength.
Various ranges of the electromagnetic spectrum in terms of physical interaction with matter appear as self-similar octaves like those found in music. For example, the frequency range through to microwaves primarily affects "free" or weakly bound electrons to cause the generation of electrical currents in an antenna, which is then amplified to reproduce the original output signal. Beyond the microwave frequency, electromagnetic radiation begins to interact on a molecular level. In the next octave of frequencies the interaction is focused down to the atomic level. And the next level is that of the nucleus.

pump those transitions with any existing source, to produce a population inversion, that would not destroy the conditions that make the Mössbauer effect possible. So that approach has been discarded. Right now, everyone, our Russian friends as well as ourselves, is looking at a hybrid approach where we prepare a long-lived transition and then, with a small amount of energy, pump it into a state that could emit a Mössbauer line and lase. That way, by reducing the pumping energy, we could still maintain the condition for a Mössbauer effect.

An essential feature we have to have is a recoil-less line. For that, we have to have a solid host that is still solid after we have pumped. The approach, therefore, is to reduce the pumping requirements as much as possible by finding a transition where there is a long-lived nuclear state very close to the one which you want to lase. That, of course, brings in a whole set of problems that we are only beginning to solve now.

The main problem up to now has been convincing people that it is worthwhile trying to solve those problems, that there is a chance that you might succeed; that has been the main obstacle. Now, the obstacles are the physical ones of solving those problems of finding the right nuclide, separating the isomer that you have pumped radiochemically, carrying out that transfer step, and ensuring that you can do that under conditions where you will still have the Mössbauer effect.

Q: Could you describe what you've done recently?
Baldwin: What we have done so far is only the first step. We have taken a typical case, one where we had enough information at the beginning so that the experiment could be straightforward, and we have used an optical laser to separate two different states of the same nuclear isotope, the same nuclide. We have demonstrated that, in principle, at least in this one case, we could separate a long-lived isomer from other products of the nuclear reaction. That way we could prepare the pure material that would later be used for a laser.

However, what we have separated is unlikely to be a graser candidate. It happened to be a nuclide, mercury-197, where it was a very straightforward process to demonstrate that the principle of isomer separation, that we would use ultimately on any graser, was a feasible principle. So that answered one of the major questions: Can you separate an isomer if you've prepared it radiochemically? However, there still remain the problems of transferring rapidly from an isomer level of long lifetime to the short-lived level of the laser. First we have to have the candidate nuclide; at present, we don't have one.

Q: Could you explain the radiochemical process?
Baldwin: In the radiochemical process there are many options. Nuclear reactions have a wide variety of types. Perhaps the most straightforward one would be to activate something in a reactor. However, in the case of mercury-197, we prepared it by bombarding gold with deuterons from an accelerator. Accelerator, reactor, fission products—any such way by which radioisotopes are prepared might be useful. What the method for working grasers will finally be, will depend on the results of our search for candidate nuclides: depend on their chemistry, on their nuclear properties, and on the availability of the raw material.

Q: Are there any prospective candidates at this point, any ones that look like they have a possibility?
Baldwin: There are no specific nuclides that we have identified, for a very good reason: We don't yet have the resolution that is needed to establish the energy levels accurately. We know that we are more likely to find them in certain regions of the periodic table. That is being worked on and will be reported in due course. At this time, however, we have only certain areas of the nuclide chart where a more intensive look has to be made. So far, this is all theoretical; the experimental work that will confirm that there is indeed a nuclide with a proper level scheme won't be ready for a year or so.

Q: What sort of resolution are you looking for?
Baldwin: That's the problem. The direct measurement of gamma-ray energies involves detectors whose resolution rarely is better than about 500 electron volts. We'd like something with 10-electron-volt resolution. And that's a very tall order for the instrumental people.

Q: Yes, aren't the gamma rays in a range of millions of electron volts?
Baldwin: Actually, because of the requirement that you have a Mössbauer effect, the gamma rays we're interested in for the graser would have to be somewhere between about 5 and 100 kilovolts. That would be wavelengths from about 2.5 angstroms down to about a tenth of an angstrom. For that you're going to have to use some other principle, because the Mössbauer effect is pretty much limited to those lower gamma-ray energies, and it alone gives you the sharp, intense line with the very high interaction cross section you'd need in order to stimulate it.

Q: From what you said, there appear to be four steps to a gamma-ray laser. The first would be the location of a long-lived isomer, then the ability to separate and concentrate that isomer, then to be able to form a crystal, a Mössbauer crystal out of that isomer. . . .
Baldwin: Yes, the crystal is very important. I'd like to talk some more about that in a minute. But the real $64 question is: Once you've made that crystal, can you carry out the transfer step to a lasing level?

Q: In other words, can you pump it?
Baldwin: Yes. And in order to firm up the numerical requirements that would guide a candidate search and would guide a transfer operation, we have to coordinate all of that

Graser crystals: The harmonic properties of crystals are currently utilized to transform the frequencies of electromagnetic radiation in the optical spectrum. For grasers, both the generation and propagation of the output, coherent gamma ray pulse will strongly depend on these crytaline harmonic properties. Shown above is Dr. Stephen Craxton, who demonstrated that KDP crystals could frequency-triple infrared light into light at ultraviolet wavelengths.

and make kinetic studies that look at the probable behavior of hypothetical systems.

Gradually, as we acquire more information, we'll begin to look at more and more real systems. But as we are doing those kinetic studies, we may revise our requirements considerably for the candidate nuclides and for the hosts in which we have to place them, as well as for the crystal structure that those hosts have to have. All of those are very closely interrelated problems. It's an extremely interdisciplinary subject.

Q: You are ranging from nuclear physics to laser atomic physics to crystals.

Baldwin: That is one of the main reasons why we have been so slow about getting around even to looking at this. Scientists tend to overspecialize these days, and people who are skilled in laser technology have no time to study nuclear physics, and vice versa. That barrier is breaking down though, and I am happy to see that there are people beginning to look at both fields, because that's what we need.

There's chemistry, crystallography, nuclear physics, laser physics: There's hardly a branch of technology here that doesn't enter in. For example, one of the subjects that I am particularly turning my attention to now is the optical properties of crystals for gamma rays, and whether we can preserve those while we pump. That brings in the question of how does a solid in an ordered structure respond to the energy that you are suddenly going to pump in? Because of inefficiency of the transfer process, that is going to heat the solid, which is why that transfer step has to be low energy. It's also why the nucleus that we are going to pump has to have a very close pair of states of quite different lifetimes. That, of course, is why the nuclear physicists, then, are going to have to develop a higher resolution type of spectroscopic application. So you see how closely coupled all these things are.

Q: I understand that with ordinary visible photons, you have a photoelectric effect, and then at shorter wavelengths, you begin getting into inverse Bremsstrahlung absorption, and then later on a Compton scattering becomes primary. What is it that allows a gamma ray to actually be able to propagate through a crystal?

Baldwin: First of all, in the Mössbauer effect, we observe resonant interactions of gamma rays with nuclei in which the cross section can be hundreds of times higher than the cross sections for the photo effect and the Compton scattering. That's because the line is extremely narrow, has nearly its natural width, and the cross section for stimulated emission goes as the square of the wavelength. Now, the cross section for the photoelectric effect varies as the cube of the wavelength. For the Compton effect, it varies directly with the wavelength. So there's a region where, before the Compton effect takes over, there is actually less nonresonant loss due to the photo effect than gain from stimulated emission. As you go to shorter wavelengths, the situation actually gets better there for a while. But eventually, because of the Compton effect, which does vary directly with the wavelength, and because stimulated emission cross section varies with the square, eventually Compton scattering is going to prevent lasing. The losses will then exceed the gain.

That's not true in this region from a few kilovolts up to almost a million electron volts (MeV). I wrote a paper on that about 12 years ago, on whether there was a high frequency limit to laser action. The conclusion was that, if there is one at all, it's got to be somewhere above 1 MeV, but not very far above it. So we've got a long way to go yet.

Q: To get the isomers into a lasing state, wouldn't you have to pump the crystal very efficiently so as not to destroy it?

Baldwin: That's right. It would have to be done very efficiently. We have some new ideas here that also come from crystal optics. So let me talk about the properties of crystals for a moment. In the somewhat longer wavelength region where the x-ray laser people are working, you have no choice but to work with plasmas. In the gamma-ray region, however, we're hoping that by taking advantage of this property of long-lived isomers that have another state close together, one can lase and still preserve the crystal.

A crystal with its ordered array of atoms and nuclei can act as a resonator. For longer wavelength x-rays, they're going to have to make resonators by making artificial crystals with large lattice spacings that correspond to those longer wavelengths. In the gamma-ray region, the wavelengths are comparable to crystal dimensions and crystal spacings; that, of course, is the basis for x-ray diffraction, and we've known of that for almost 75 years. Now, in a very well-ordered crystal, the Bragg reflections that take place can set up modes which are just like the standing wave modes in the distributed feedback resonator that is used in some kinds of lasers. The crystal itself then becomes a very high Q resonator.

Those modes that will be guided down between the lattice planes of the crystal will avoid the atoms, so that they're not producing photo electrons, which would deplete the wave. Still, at the same time, they do undergo magnetic interactions. Most transitions of low-energy nuclei are magnetic transitions rather than electric. So the wave stimulates nuclei, but is not depleted by the photo effect. That was pointed out about 10 years ago by George Trammell and his people at Rice University, and we collaborate closely with them. I certainly would like to give credit to their contribution, because they've been very helpful in this, just as Michael Feld and his people at MIT have been helpful to us on the isomer separation. We are collaborating with those people and we hope that we'll open up other avenues of collaboration where the expertise is needed.

Q: What would this crystal resonator do for you?
Baldwin: At the same time that the crystal resonator reduces those photoelectric absorption losses, it actually enhances the magnetic interaction with the nuclei. The practical effect of it is that if a graser body is a perfect crystal, the requirement for lasing—the number of nuclei that have to be transferred into that host crystal—can be lower by a factor of almost 20 or so, than it would be in bulk material. So that is a gain of a factor of 20.

There's a lot of work going on now, and there is even a new journal devoted to the study of superlattices; that is, artificial crystals that are built up with a large lattice spacing, by these micro-fabrication techniques that have become so important in electronics. Suppose now that, to build our graser material, we have a host crystal which is a very good crystal, and one that happens to be such that we can dope it with the isomer that we have prepared radiochemically. We dope it in a periodic array, which superimposes, then, on the regular crystal lattice a much larger spaced crystal. We adjust that spacing so that it is a resonator for the radiation we need to induce the transfer. For the same reason that we have reduced the excitation requirements for lasing, we have increased the effectiveness of the transfer radiation. We have also concentrated it into a mode that interacts strongly with the nuclei we want to transfer and only weakly with other atoms. We are hoping, then, that that will reduce the requirements for transfer. We will then have attained a double advantage on the transfer step, because we don't have to transfer as many nuclei, and whatever radiation we use for transfer will be used more efficiently.

Now, that's the hope. I think that you can see from what I've been saying that this is by no means a simple, straightforward problem where there's an easy "quick fix." We're not going to make a graser tomorrow. I don't think that I'll even be around by the time that we have finally solved all of these problems, but I think that the time is long overdue for us to get busy and solve them.

Q: Have you seen the work of Dr. Charles Rhodes, of the University of Illinois?
Baldwin: Yes, I have, and in fact I'm very interested in that. If what he's saying about what he is doing is correct, this may give us a new approach to interlevel transfer. In fact, we want to do some experiments where we try to duplicate the conditions that he has and look for the excitation of the nuclear state.

Q: You mean his multi-photon absorption by atoms has a possibility of being extended to the nucleus?
Baldwin: The only problem, you see, is that we need an example of a nucleus like our storage nuclide for experiments. There is one particular case: Uranium-235, of all things, has its first excited state at only 75 electron volts above the ground state. Rhodes claims that he has observed multi-photon absorption of several hundred electron volts, so that he excites x-rays from inner shell vacancies. We want to look and see if we can excite that uranium-235 nuclear state. If so, then the transfer step should be feasible.

It may be a very difficult thing to do. It's an electric octupole transition that has a very, very narrow radiative width, but perhaps through this collective mechanism of Rhodes we can excite it. We have a consultant at Duke University, Larry Biedenharn, who is working on the theory, and he believes that we really can excite that nuclear state. Peggy Dyer, who has been working here with me on isomer separation, Bob Haight, and Steve Wender are planning an experiment to see if they can excite that uranium-235 state with a set-up like Charles Rhodes has.

Q: It sounds very exciting. You are using the frontiers of a number of areas.
Baldwin: As a matter of fact, keeping up with the literature that might bear on this is getting to be a major preoccupation. I spend about a half-hour every day going through the recent literature, and every once in a while I come up with a gem that immediately suggests a possible route to a solution of some problem here. But don't let me minimize the difficulty of all of these problems. We're trying not to make any promises that we don't think can eventually be kept. We have an honest, objective program; we have nowhere near enough manpower, and certainly not enough money, to attack on all of these fronts that were presented here. We need other people to be interested. We need recognition that scientific dividends will come from this work, not just the directed-energy applications that military people might be interested in, but the scientific applications as well. They justify a really broad program of research. I think it's going to come, but I can't say when, and I certainly don't want to minimize either the difficulties or the enormous payoff that success will bring.

GLOSSARY

Ammonia maser. A device for generating coherent microwaves by means of stimulated emission. MASER is the acronym for Microwave Amplification by Stimulated Emission of Radiation. The first (1954) generators of high frequency (as opposed to vacuum tubes, thyratrons, etc.), coherent electromagnetic radiation were masers. When, in 1958, their extension to optical frequencies was proposed, the term "optical maser" was introduced. Eventually, the term LASER (Light Amplification by Stimulated Emission of Radiation) won out.

Bragg reflection, Bragg angle, etc. Bragg's law for reflection and refraction of radiation emerges when the incident electromagnetic radiation wavelength becomes significantly less than the interatomic spacing (D) of the planes of a crystalline material. At wavelengths significantly greater than D, all angles of reflection and refraction are apparently equal. When the wavelength is less than D, only specific wavelengths are permitted, as given by

nw = 2D sin x. Where n is any whole number, w is the incident radiation wavelength, D the interatomic spacing of crystalline planes, and x is the permitted angle.

Doppler effect. Like the train whistle which varies in pitch as the locomotive approaches or leaves the station, the wavelength of the radiation emitted by an atom or molecule in a gas or a solid will vary depending on whether it is coming toward or receding from the relatively stationary observer.

Electron volt. A unit of energy. It is also used as an equivalent unit of mass and even temperature. One electron volt (eV) is roughly equivalent to one billionth of a proton mass, 1.6×10^{-19} joules, 11,000° K.

Electric octupole transition. Atomic and nuclear dynamics are sometimes represented as oscillations of a spherical surface. These can be either simple mechanical motions or changing concentrations of discrete electrical charges, and/or continuous electromagnetic fields. The normal modes for these spherical oscillations are, in general, determined by the Platonic solids. For example, in an electric octupole transition, the eight points determined by the 8 vertices of a cube inscribed within the oscillating sphere define 4 diameters along which the greatest amplitudes of the octupole oscillation is seen.

Ground state. In a cyclic or, rather, harmonic system, the ground state is the least action (a.k.a. minimum energy) state in which the internal dynamics of the system appear to be force-free. A more rigorous definition would include that the physical system, such as an atom, nucleus, or force-free plasma filament, is configured to be commensurable with the prevailing curvature (quantum structure) of space-time. When excited above such ground states, the system has the potential of transforming the transfinite ordering of the prevailing space-time curvature. In the ground state, harmonic orderings are never congruent with divisions determined by the so-called rational numbers. Only transfinite, or at best, transcendental orderings obtain.

Isomer. In nuclear physics, an isomer is a nucleus whose chemical and isotopic configuration remains essentially the same, but whose harmonic structure has been driven into an excited state, like that of the electric octupole transition.

Mössbauer effect. Normally when an excited nucleus emits gamma rays, the nucleus experiences a significant recoil motion like that of a firing cannon. This motion generates a Doppler shift in the wavelength of the emitted gamma rays. In 1957, R. L. Mössbauer discovered that if the emitting nuclei are placed in a properly configured crystal, the crystal lattice as a whole will absorb the recoil. This means that the Doppler shift is significantly suppressed.

Photoelectric effect. The least action (minimum energy) generation of electric currents in matter by incident electromagnetic radiation. For the existing spectrum of chemical elements, as determined by the presently prevailing space-time curvature, the ultraviolet portion of the electromagnetic spectrum produces photoelectric currents most efficiently. It follows that this wavelength range is also, therefore, most efficient for inducing changes in chemical potentials.

Spontaneous emission. The emission of a photon by an atom in an excited state without any apparent external stimulation. Actually, the transition involved is from a state in which the atom has a greater potential for transforming the curvature space-time to a force-free configuration congruent with the prevailing space-time curvature. The more appropriate term would be quantum space-time induced emission.

Stimulated emission. A process in which a sample of atoms or molecules in excited states are externally induced to emit photons coherently. In other words, individually excited atoms or molecules are macroscopically ordered into force-free geometries capable of producing potential transformations in the curvature of space-time, such as seen in laser-induced nuclear fusion. Alternatively, the resulting net laser pulse can be thought of as being the creation of a new quantum of action, not previously available to the previously prevailing, lower transfinite ordering of quantum space-time.