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The Laser and How it Happened

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I'm going to discuss the history of the laser and my own personal participation in it. It will be a very personal story. On the other hand, I want to use it as an illustration of how science develops, how new ideas occur, and so on. I think there are some important issues there that we need to recognize clearly.

How do new discoveries really happen? Well, some of them completely by accident. For example, I was at Bell Telephone Laboratories when the transistor was discovered and how? Walter Brattain was making measurements of copper oxide on copper, making electrical measurements, and he got some puzzling things he didn't understand, so he went to John Bardeen, a theorist, and said, 'What in the world is going on here?' John Bardeen studied it a little bit and said, 'Hey, you've got amplification, wow!'. Well, their boss was Bill Shockley, and Bill Shockley immediately jumped into the business and added a little bit. They published separate papers but got the Nobel Prize together for discovering the transistor by accident.

Another accidental discovery of importance was of a former student of mine, Arno Penzias. I'd assigned him the job of looking for hydrogen in outer space using radio frequencies. I'd been doing radio spectroscopy and I thought, well, there's a chance of maybe finding hydrogen out there with radio waves, so he looked. He didn't find hydrogen but he did a good job, got his PhD, went on to Bell Telephone Laboratories and there joined up with Bob Wilson and they continued to look. They were using a maser amplifier, which was the most sensitive amplifier available – and it still is. They didn't find hydrogen but found a low intensity continuous radiation coming in from all directions, radio radiation coming in from all directions in the microwave region. What was that? Well, they looked at it and talked to other people and published it, and people recognized that it was a residual of the original Big Bang of the Universe, the first real demonstration that yes, there was a Big Bang. The Universe did have a beginning and this was the discovery of the beginning of the Universe by accident.

Many discoveries happened that way but some are the result of a steady, directed effort and the latter is the case of the laser. In both cases it is necessary to use great care, thoroughness and intensity. You see, Walter Brattain was doing very careful work and so was Arno Penzias, and they made great accidental discoveries. In the case of the laser, it came about as a very systematic effort on my part. Why did I want to do this? Well, in 1939 I got my PhD and I wanted to do physics research at the university, but there were no interesting university jobs at that time, so I took a job at Bell Telephone Laboratories. They initially let me do some physics research but pretty soon the war was coming on so they said, 'We want you to start building a radar system'. Oh dear, I had to become an engineer and design a radar system! They wanted a radar system with shorter wavelengths than anything they had, 1¼ cm – about half an inch – wavelength. Well, OK, so I had to do that and learned a lot of engineering, which has become very valuable to me. However, when we almost finished building it, we discovered that wavelength is absorbed by water vapor in the atmosphere. Oh dear, the waves wouldn't get through the atmosphere, so we had to discard the whole thing. As a result of that I decided maybe I would try to study and check out this water vapor, so in the laboratory I made measurements of water vapor absorption at this wavelength. I recognized then a new kind of spectroscopy in the radio region, very precise. We had very narrow bandwidths, with very precise frequencies, and so I started studying other molecules, including ammonia and so on. Bell Laboratories let me do that and particularly after the war I could stop engineering and do physics. I studied molecules and got great precision not only about molecular structure, but also the nature of the nuclei in the molecules, their spins and shapes. I found I could measure how the nuclei differed from sphericity, for example, looking at the spectra. I published and that became important physics, important enough that I was offered a job at Columbia University to continue to do such work. OK, well, that's great. So I got to Columbia University and continued to work. I recognized, though, that I really wanted to get on down to shorter wavelengths. Now, electronics could, at that time, produce fairly shorter wavelengths, down to about 2 or 3 mm but not much shorter. I wanted to get on down to still shorter wavelengths, maybe down to the infrared – that is below 1 mm as we define infrared. I had my students try various electronic things, but they didn't work. Now, the Navy knew that I was interested and the Navy wanted to get to shorter wavelengths too, so they asked me to form a national committee to find some way to get to shorter wavelengths. I formed a national committee and got a lot of important scientists and engineers together. We travelled all over the country visiting various laboratories and talking with people. After a year's time we hadn't found any answers about how to produce shorter wavelengths. At our last meeting in Washington D.C. we had to write a report saying sorry, we hadn't found anything. I woke up early in the morning worrying about it. I went out and sat on a park bench on a lovely sunny morning and I thought, 'Why haven't we been getting any ideas? Now, what can possibly do this?' I thought, well, of course molecules and atoms can produce short waves but, of course, thermodynamics says they can't produce more than a certain intensity. Intensity depends on the temperature at which you have the molecules and atoms, so you can't get much intensity. Wait a minute! Wait a minute! They don't have to obey thermodynamics. We can get molecules in states that don't follow thermodynamics. Thermodynamics says you have to have more molecules in a lower state than in an upper state, so there's more absorption than emission and that limits the total emission that they can produce. The upper states drop down and give energy, the lower states, of course, absorb energy. Hey, wait a minute, we can pick out molecules mostly in the upper state. If we get enough of them in the upper state they can amplify, because they will all drop down and nothing absorbs, so they'll all emit radiation.

Now, at Columbia, Professor I.I. Rabi had, for some time, been doing molecular and atomic beam work where he separated states of molecules and atoms by deflecting them in a beam. The beam was deflected by electromagnetic fields so you can pick out various states, and I recognized that that was one way I could do it. I persuaded Jim Gordon, a student at Columbia, to do this for his thesis. We worked on ammonia molecules because I thought I should do it in the microwave region first – I wanted to get into the infrared, but I thought I'd do it in the microwave region first because I had a lot of microwave equipment and that was the simplest thing to do. So Gordon and I worked on it. We were building equipment to try to send the ammonia molecules in a beam, deflect them so that the high energy ones could be focused into a cavity and the low energy ones could be thrown away. Well, Gordon was working on this for a couple of years. But then Professor Rabi, who was the former chairman of the department, and Professor Kusch, who was then chairman – and they were both excellent physicists, they got Nobel Prizes – came into my laboratory and said, 'Look Charlie, you've got to stop! That's not going to work, we know it's not going to work, you know it's not going to work, you're wasting the department's money, you've got to stop!' Fortunately, in a university, a professor can't be fired just because he's stupid. He can be fired if he does something morally wrong but not simply if he's stupid and has done something scientifically wrong, so I knew they couldn't fire me and I said, 'No, I think it has a reasonable chance of working, I'm going to continue'. So they marched out of my lab, angrily. Well, we kept going and about two months later Jim Gordon came to my classroom and said, 'Hey, it's working!' Well, all my students and I went to the laboratory to see this thing that was working. We were sending enough molecules into the cavity, they emitted some radiation, the radiation bounced back and forth and stimulated the other molecules to give up more energy and so it produced an oscillation. This oscillation was a very, very pure frequency and wow, that was exciting and a lot of people got interested. I was due to have a sabbatical leave, so I took a sabbatical leave and went to Paris. In Europe I knew Aage Bohr, who had been at Columbia with me (he died recently, his father was Niels Bohr, a very famous physicist and both of them got Nobel Prizes). So I went to visit Aage Bohr and I was walking along the street with Niels Bohr and he asked me what I was doing. I told him we had this oscillator, giving very pure frequency from molecules. 'Oh', he said, 'No, no that's not possible'. I said, 'Well, we've got it'. And he said, 'No, you've misunderstood something, no, no'. He just wouldn't talk to me about it, 'No, no, you're wrong'. Why was that? I suspect he was thinking of the uncertainty principle. You send a molecule through a cavity, and if you try to measure its frequency, the uncertainty principle says that the frequency can be measured only with an accuracy of one over the time that it passes through the cavity, and that's pretty short. That's the uncertainty principle. Bohr was sure it wouldn't work and that it didn't give such pure frequencies. He didn't recognize I was using a big collection of molecules and I had feedback and so on. Any engineer recognizes that feedback amplifiers, or feedback oscillators, can give very pure frequencies. Any engineer knows that but Bohr didn't recognize this and he just shut me up. He wouldn't listen.

There was also John von Neumann, a very famous mathematical physicist. I ran into him at a cocktail party and he asked me what I was doing. I told him we had this very pure frequency and he said, 'No, that's not possible, you're doing something wrong, you haven't measured it right, you misunderstand'. 'No, I've got it!' 'No, no, no'. Well, he went off to get another cocktail. About 15 minutes later he came back and said, 'Hey, you're right, tell me more about it!' Somehow he had suddenly woken up to the idea. He was a little bit more of an engineer than Bohr was. Well, you see, getting engineering and physics together was important. As I said, the field became very exciting with a lot of people working on it and it grew and grew. I had gotten the first one going in 1954 and after about a year and a half I said, 'Well, I really want to get on down to the shorter wavelengths. Let me see how I'm going to do that, I want to sit down and see just how far down we can get in wavelength'. I sat down and wrote some notes and equations and hey, it looked like I could get right on down to light waves. Wow, right on down to light waves, oh boy! Well, the field was such a hot field then I knew I shouldn't say anything about it because a lot of people would immediately compete with me. When I was building the maser, absolutely nobody competed. People would come by and say, 'Oh that's an interesting idea', but nobody competed. The only other people doing this were the

Russians, Nikolay Basov and Alexander Prokhorov, who had an independent idea and I didn't know they were working on it and they didn't know I was working on it. They didn't actually get one going first but they got the Nobel Prize with me for generally thinking of the idea. So nobody else was interested until it got going, then everybody was interested and it was very competitive. So I decided, well, let me see what I can do first and publish something, rather than saying anything to anybody and have them immediately compete with me.

I was a consultant at Bell Telephone Laboratories and Arthur Schawlow – who had been a post doc with me and married my kid sister, which I was very pleased about – was working at Bell Telephone Laboratories. I went and talked with him, told him about it, and he said, 'Well, you know, I've been wondering about that, can I work on this with you?' I said, 'Well, sure, OK', so he worked on it with me and he added an idea which was important. I was going to send the molecules into the cavity and then the light would bounce around the cavity in all directions. But with two parallel mirrors as suggested by Art Schawlow, light would bounce back and forth only in one direction and produce a beam, a nice beam. He had that idea and he added it so we decided, 'Well, this ought to be patented but I guess we probably ought to give the patent to Bell Labs. Let's take this idea to Bell Laboratories' lawyers and have them patent it and then we'll publish a paper about it'. So he went to Bell Laboratories' lawyers, but he called me back a couple of days later and said, 'Well, the lawyers told me they're not interested in patenting that, because they say that light has never been used for communication and it wouldn't be interesting for Bell Labs, so if we want to patent it they will just give us the patent'. I said, 'Well, it just shows they don't understand. Of course it can be used for communication, they don't understand, you go back and tell them. We shouldn't take the patent away from them just because their lawyers don't understand, so you go back and tell them, yes, it can be used for communication'. The lawyers then responded, 'Well, if you can show us how we can use it for communication then OK, we will patent it for Bell Labs'. So we did that and wrote a patent, entitled *Optical Masers and Communication*. Now, we had named this original thing the maser. My students and I sat down and said, what shall we name it, and we *named* it maser for Microwave Amplification by Stimulated Emission of Radiation, MASER. That was the maser. It was an original thing and the maser became a very popular name, so Art and I wrote the patent and we called it an *Optical Maser and Communication* for the patent. The lawyers went ahead and patented it then, because we showed them how it could be used for communication, which was obvious to us.

Well, now we were going to publish, I knew if we started trying to do the experiment and make one then we would have a lot of competition and somebody else might beat us to it anyhow, so we'd better publish the theory showing how it could be done. So Art Schawlow and I wrote a paper saying how it could be done, calling it *Optical Maser*, and we published. And then everybody got interested and wow, there was a lot of competition. Everybody jumped into the field. Yes, and at that time also I had been asked to go down to Washington to head a big scientific group to advise the government. I felt, well, that's a kind of a public duty, I should probably do it, so I went down and I was vice president of this group of scientists to advise the government. I agreed to go down for two years, hence couldn't work very well on trying to build the first laser. My students were working on it and I was hoping they would get along pretty fast, but the actual first one was built by Theodore Maiman at Hughes. Now, Ted had read our paper, with a lot of other people, and everyone jumped in the field trying to build one and he built the first system. The name was pretty quickly changed from optical maser to laser, for *Light Amplification by Stimulated Emission of Radiation*. We just called it originally an optical maser but that was too long a term, so laser became the name for it and now the term is used for any wavelength shorter than 1 mm. Anything longer than 1 mm is still a maser, so we have masers and lasers. They are basically the same thing, just different wavelengths. Well, so Ted Maiman built the first one and then Javan, one of my former students who was at Bell Telephone Laboratories, built the next one with some other people working with him, William Bennet and Donald Herriot. The next one was built by another student of mine at General Electric, Mirek Stevenson, who was working with a guy named Peter Sorokin. All the first lasers were built in industry, not by universities. Why? Because they could concentrate, work hard, and furthermore, because of the maser, industry had gotten interested in the field and had hired a lot of students from many different universities working in that field, so they had young people who were interested and knew the field. Thus all the first lasers were built in industry. As they were built, there was much growth in the field and a lot of people contributed different things. We had originally thought of lasers being produced in a gaseous discharge. But now they are produced by solids and in all kinds of ways, some of them are very small and some are very large. And by now there are lots of scientific things that have been done with lasers and masers. There have been thirteen Nobel Prizes in addition to the original prize for the invention – thirteen Nobel Prizes based on the use of masers or lasers as a scientific tool, so it has produced an enormous amount of science for which

I'm very pleased. They provide very high precision frequency as atomic clocks, they can measure distances very, very precisely. Even long distances can be measured precisely; we have measured the distance to the moon to about 1 cm accuracy (half an inch accuracy in the distance to the moon).

Laser beams also produce great directivity. So there's a lot of science and I'm just delighted to see all the good science that has been produced, as well as a lot of industry. Now, you see, the field I was working in, microwave spectroscopy, was not of interest to industry. They said, 'That's just physics and won't pay off', but it did pay off and that's typical of science, of course. New ideas come along and every once in a while there are lots of commercial applications. Well, the laser is now producing industry of some tens of billions of dollars a year at least. There is lots of industry. Lasers come big and small and do all kinds of things in industry. There are a lot of medical applications. Light now is a fantastic communicator. It has such a wide bandwidth, you can get about a billion channels of communication on one beam of light. It's just changed communication enormously. It's used in the military. It's not powerful enough to produce a weapon exactly, but it can direct weapons and it's used for pointers. It's also used for cutting and welding and manufacturing, all kinds of things, both very large and very small.

The biggest laser now is what's called the National Ignition Facility. It's built in order to ignite uranium to make uranium energy, to produce nuclear energy by shining intense light on these nuclei and allowing them to burn. This light intensity produces the highest temperature anyone has ever achieved. The NIF, National Ignition Facility, built by a laboratory of the University of California, has 192 laser beams. It's about 30 m high, 192 laser beams all focused together into a diameter as small as about 1.5 microns, just a couple of light wavelengths in size, and the total energy going in is 600 thousand billion watts. Just think of the temperature that represents, higher than any temperature anybody's ever achieved before. Not only do lasers provide very high temperatures, they also produce the lowest possible temperatures ever achieved. And these low temperatures produced one of the Nobel Prizes, for somebody who achieved extremely low temperatures with lasers. Thus lasers have an enormous variety of applications scientifically and commercially and, again, as I say, I'm delighted. Just think about the Bell Laboratories' lawyers, how they didn't think it would have commercial applications, certainly not communications applications.

Everybody was initially surprised about the possibility of masers producing lightwaves. However, once we published the paper on the possibility of doing this, then a lot of people jumped into the field, including industry, and recognized some of the applications, but not all of them. I recognized a lot of the applications but one I missed completely: I didn't realize the medical applications, but those have been very widespread. Now, let's look at this. It is fairly typical in the development of science – it is now a very big science, it's very big industrially, it was completely ignored by industry initially – not a field of interest – but it's become very important. Well, we must be open to new ideas. Also, note that somebody tried to stop me, even important physicists tried to stop me. Industry wasn't interested at all, important physicists told me it wasn't going to work, and even after I had it going some important physicists told me *no*, *that's impossible*, *that's crazy*, *you don't understand*, *you've done something wrong*, *you don't know what you're doing*. New ideas are new, we've got to be open to new ideas and encourage people to explore new things, even the things that we're not very sure are going to work, or we think won't work, but it's good to explore. Another thing to remember is unpredictability. We frequently can't predict new things. And so we must again allow people to stick to new possibilities, explore new things, because we don't know where we are and what we're missing. In fact, all the scientific information needed for lasers was recognized as early as about 1920. We knew all the physics involved by as early as 1920. But the only possible suggestion of this, before we made things work, was about 1922. Richard Tolman, a theoretical physicist, was writing about quantum electronics and the excitation of atoms and said, well, of course, if you had more atoms in the upper state than the lower state then they would increase the energy of the waves a bit, but he went on to say that it would probably be very small, and this was just in the middle of a paragraph where he was discussing the theory of it all, so nobody paid any attention. He didn't pay any attention to it and nobody said anything more about it from 1922 until we had the idea and got it going, and so the first laser was built in 1960, about 40 years later. Humans wasted 40 years because we didn't use the theory that was there. The basic theory was all understood but nobody applied it, nobody explored it, nor recognized it.

So what are we missing now? Let's think about it, let's explore, be open-minded, encourage young people to look at new things. That, as I say, is kind of a history of how science develops. Many, many people have contributed to this idea, many people have done things which I didn't imagine initially, and they've added on things. That is what allows science to grow. We all work together, and now I want to emphasize interaction among scientists.

When I went to Paris on a sabbatical leave – I mentioned Niels Bohr, and so on – I ran into one of my former students who was there and was working on electronic spins. He found that, if he put some of them up in energy in a magnetic field, they would stay up for some time. I said, 'Hey, wait a minute, maybe we can make a maser using electron spins in the upper state. We can amplify and we can tune it, and thus get a tunable amplifier with electron spins'. So we published a little paper about that possibility. Then Nicolaas Bloembergen, who was at Harvard, read this and had a still better idea. Because he had been working with electron spins, with two of them joined together so they could have three energy states – an upper level, a middle level and a lower level – he recognized that you could pump from the lower level to the upper level and then fall down to the middle level and get amplification. So that produced the first really good maser amplifier. Then I went to Japan after that and I continued my sabbatical leave. I ran into a biologist that I had known at Columbia, Francis Ryan, and I said, 'What are you doing?' And he said, 'You know, I've been trying to work out a theory of the fluctuations in the populations of microorganisms. Microorganisms can die or they can double and multiply and I'm trying to figure out the equation of how they vary in numbers'. And I said, 'Wait a minute, that's just what I want!' To get the fluctuations in a maser amplifier I had to add one term, namely spontaneous emission – stimulated emission is like birth of a new microorganism, not just splitting, but you can automatically produce the birth of a new photon by just emission – and so I added one term to the equation and we worked out the answers to that equation. That allowed me to provide a theory of the fluctuations of the maser amplifier and oscillator, as well as fluctuations in the number of microorganisms. That is another example of interaction between science and scientists, you see. These are just examples of the importance of interactions of different fields and different scientists. We must talk together, we must let fields interact. The engineering experience I had was enormously important in producing a new field and now there are more and more people who perhaps know the whole thing about lasers but what is it we are missing now. We missed lasers for forty years, what are we missing now? We must be open minded, encourage new ideas, encourage exploration and hopefully produce a lot of new interesting results, scientifically and economically. Thank you.