CHARLES HARD TOWNES

The American physicist Charles Hard Townes was born in Greenville, South Carolina, USA on July 28, 1915. He received the Nobel Prize for physics in 1964 for fundamental work on the maser and laser along with Nikolai Basov and Alexander Prokhorov. Townes attended public school in his hometown and later received Bachelor degrees in 1935 in both physics and modern languages at the age of 19 from Furman University, also in Greenville. After obtaining a master's degree in one year from Duke University, Townes began his dissertation at the California Institute of Technology studying isotope separation and the spin of the carbon 13 nucleus, finishing successfully in 1939.

An eight year tenure at Bell Labs followed during which Townes turned to war-related topics, in particular radar bombing technology using microwaves. However, he also delved into the application of microwaves to spectroscopy, an area of research which would define his further career.

After Bell Labs, Townes became associate professor of physics at Columbia University in 1948 and continued his use of microwaves to study their interaction with atoms, molecules and nuclei. During this time, in the early hours of April 26, 1951 on a visit to Washington, DC for meetings, Townes sat in a nearly empty downtown square and sketched out his ideas for the maser on the back of an envelope. Interestingly, most of the physical principles of how a maser should function were already clear to Townes, and to others as well. Townes' 1964 co-Nobel Laureates, Alexander Prokhorov and Nikolai Basov were independently coming to similar conclusions in Russia, albeit somewhat later. In fact, many who worked on the maser at this time have commented that it really could have been invented at any time in the 1920s, 30s or 40s because the last piece of the physics puzzle needed to build a maser had already been published in 1916.

The maser functions on the principle that a photon (light) which interacts with an active medium (molecule or atom) can cause the emission of a photon exactly like itself if the system is in an excited state before the interaction. If the photons are in a resonant cavity with reflecting walls they may oscillate back and forth, repeatedly traversing the active medium and causing the further emission of photons. In this way a single photon can cause an avalanche of new photons, each with the same characteristics as the original photon. The result is an intense beam of coherent electromagnetic radiation.

In 1916 and 1917, Albert Einstein published two articles on the quantum theory of radiation (zur Quantentheorie der Strahlung) while investigating the direct derivation of Planck's radiation formula, $\rho = \frac{\alpha}{e^{\frac{\epsilon_m - \epsilon_n}{kT}} - 1}$ with $\alpha \sim \nu^3$ and $\epsilon_m - \epsilon_n = h\nu$ (all equations here are in Einstein's original notation). He was attempting to use only quantum mechanical principles of the interaction of light and matter and the Boltzmann distribution from statistical mechanics, $W_n = p_n e^{-\frac{\epsilon_n}{kT}}$. In exploring the interaction of photons with matter, Einstein introduced the concept of stimulated emission of a photon from an atom or molecule as well as using the already well-known phenomena of photon absorption and spontaneous photon emission.

Einstein reasoned that just as an electron in an atom (or molecule) jumps from a level Z_n with energy ϵ_n to a level Z_m with energy ϵ_m ($\epsilon_m > \epsilon_n$) by absorption of a photon with energy $h\nu = \epsilon_m - \epsilon_n$, an electron can also be made to jump from level Z_m to level Z_n in the presence of a photon with energy $h\nu = \epsilon_m - \epsilon_n$, during which a photon is released. That is, the existent electromagnetic field *stimulates* the electron transition in the system and the photon released has the same energy, direction, polarization and phase as the stimulating photon and leads to an amplification of the electromagnetic field.

Thus, an atom in thermodynamical equilibrium described quantum mechanically will, according to Einstein, be exposed to absorption as well as spontaneous and stimulated emission of a photon according to the following equation:

$$p_n e^{-\frac{\epsilon_n}{kT}} B_n^m \rho = p_m e^{-\frac{\epsilon_m}{kT}} (B_m^n \rho + A_m^n)$$

where the left hand side of the equation represents photon absorption and the right hand side stimulated and spontaneous emission. A_m^n, B_m^n, B_n^m are the Einstein coefficients for spontaneous emission, stimulated emission and absorption, respectively.

The inclusion of the factor for stimulated emission in the equation leads, after Einstein's further calculations, immediately to the addition of the "-1" after the exponential in the denominator of Planck's radiation formula, $\rho = \frac{\alpha}{e^{\frac{\epsilon_m - \epsilon_n}{kT}} - 1}$. And this "-1" is precisely what differentiates Planck's formula from Wien's original radiation formula, $\rho = \alpha \nu^3 e^{-\frac{h\nu}{kT}}$, a solution to black body radiation known to be true only for high photon frequencies or low temperatures (regions where the "-1" becomes insignificant).

This fact partly explains why no scientist had had the courage to tackle building a laser. Many theorists were convinced that Einstein's addition of stimulated emission to his equations was only a mathematical trick to derive Planck's relation easily and correctly. There was no evidence at the time for such processes because in systems in thermodynamic equilibrium, stimulated emission will always play only a negligible role.

However, Einstein may have considered the phenomenon of stimulated emission beyond that of a theoretical tool. Instead of seeing a photon as able to excite an atom (or molecule), it is in fact much more general to consider a photon able to interact with an atom by forcing it to change, or oscillate, between energy states. Whether from a lower to a higher state or *vice versa* depends on which state the system is in before the interaction.

Another hurdle to building the maser was provided by those who had helped to develop quantum mechanics in the 1920s, in particular, those influenced by the uncertainty principle. At the time when Townes built the first maser, the ammonia molecules he used as the active medium traversed the resonant cavity in which amplification took place in less than one ten-thousandth of a second, implying they must emit radiation in still less time than that. According to the uncertainty principle, the shorter the time in which an emission process takes place, the larger the associated bandwidth of the radiation. The theoretical quantum physicists did not think it possible to have a short emission time and a highly monochromatic source as Townes was suggesting. However, Townes also had the power of experiment on his side and could demonstrate quantitatively that his device was working just as he had reported. In spite of this many physicists remained forever unconvinced.

But what Townes realized that April morning in Washington, DC was that neither the questioned existence of stimulated emission nor the restrictions of the uncertainty principle was the problem which needed solving. Inversion was the problem. Stimulated emission could only produce an amplification of light in the active medium if more (ammonia) molecules where in an excited state than in the ground state, known thermodynamically as inversion. Using the nomenclature above, there must be more molecules in the upper state Z_m than Z_n. When a photon traverses a cloud of molecules with an inverted population of energy states, there is a greater probability that the atom cause stimulated emission of a photon exactly like itself than that the photon be absorbed. A strengthening of the electromagnetic field results. Mathematically, such a population inversion would also exist if the absolute temperature, T, were less than zero. For this reason, such a situation is also referred to as having a "negative temperature."

So how could one achieve this inversion? Because in thermodynamic equilibrium the lower energetic state is always more highly populated, Townes began to consider systems not in thermodynamic equilibrium. For instance, at high temperatures the number of molecules in an excited state increases. However, Townes calculated that the temperature needed to achieve the required amount of inversion with ammonia molecules was so high, it would lead to dissociation of the atoms composing the molecule.

And then he realized the answer lay in a result from Isidor Rabi, at the time also a professor at Columbia. Rabi was able to achieve a significant population inversion by separating naturally excited molecules from those in the ground state. In the initial working maser, Townes used a set of inhomogeneous magnetic fields to achieve the same effect.

Throughout 1951 formal plans for the first maser were drawn up by Townes and his co-workers, which they published in December of that year in the quarterly report of their Columbia laboratory. Although not an official publication, the manuscript caught the attention of other scientists. And the response was not always positive. In a famous incident sometime after the report appeared, Isidor Rabi and another senior scientist at Columbia, Polykarp Kusch, came into Townes office and said in no uncertain terms, “Look, you should stop the work you are doing. It isn’t going to work. You know it’s not going to work. We know it’s not going to work. You’re wasting money. Stop it!”

But it did work. Townes and his colleagues persisted in their research until early April of 1954 when one of Townes’ students, James Gordon, interrupted a seminar he had skipped to report the first molecular oscillator was indeed amplifying microwaves. Soon after, the group dubbed the new device **m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation, or maser. The later device, using visible light instead of microwaves and often considered to be a seperate invention from the maser, was called the laser for **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation.

Also in 1954, just after the first published report of the working maser, Nikolai Basov and Alexander Prokhorov published a report in the USSR summarizing a 1952 lecture on the working principle of a not-yet-functioning maser using CsF molecules. In hindsight it is clear that the Soviets had been independently discussing relevant concepts since at least the late 1930s. In fact, in the years after Einstein’s publications on stimulated emission, there were several other examples of others broaching the subject of amplification by stimulated emission. These include Richard Tolman at Cal Tech in 1924, Willis Lamb and Robert Retherford in 1950 and Joe Weber from the University of Maryland who published a report on the relevant concepts in 1952. However, only Basov and Prokhorov’s contributions were considered important enough to win them a share of the Nobel Prize. Although their results were published subsequently to Townes', it is clear they were working independently. As for Weber, who did not share the Nobel Prize, he has since been widely recognized for his contributions to the development of the maser.

The work of Townes in the mid-1950s led to the birth of the field of quantum electronics, which continues to play an important role in our daily lives from cash registers to time keeping, laboratory equipment and surgery. Townes also remained active in the field of light amplification, which quickly became very diverse as many possibilities for active media were discovered. For example, one which is in the solid state (a crystal), can fit into a pen and has energy conversion efficiencies approaching 100%.

After Columbia Townes moved to the Institute of Defense Analysis to work on defense policy from 1959 to 1961 before moving on to become a professor at the Massachusetts Institute of Technology until 1966. Thereafter, Townes became a member of the faculty at the University of California Berkeley where he still holds his position. Also active in microwave astronomy, Townes made many contributions to the field, including the maser amplifier, which was instrumental in Arno Penzias and Robert Wilson's discovery of the cosmic microwave background.

In 1941 he married Frances H. Brown with whom he has four daughters.

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