When we are talking about the general forces of an atom, specifically weak force, one of my students asked if the changing of subatomic particles into another subatomic particle is an example of Bose/Einstein condensate/absolute zero particle. Thanks!

The short answer is no. The weak force and Bose-Einstein condensation are largely unrelated things, in the sense that the mathematics describing one doesn't in any sense describe or cause the other. The study of quantum field theory gives the most complete description of the weak force, and quantum field theory can be roughly described as quantum mechanics plus Einstein's theory of special relativity. In contrast, Bose-Einstein condensation falls in the realm of quantum statistical mechanics, which is a microscopic picture of thermodynamics, the study of large collections of particles and phase transitions, of which Bose-Einstein condensation is one; in short, think of quantum statistical mechanics as thermodynamics plus a very little bit of quantum mechanics.

One of the fundamental results of quantum mechanics (roughly, the study of small and fundamental things) is that when a particle is confined to an area, its energy can only take discrete values. A good analogy is the comparison between a ramp and a ladder: the confined particle's energy can only sit on certain rungs of the ladder, whereas a particle that's not trapped by some confining force can have any energy, like sitting anywhere on a continuous ramp. This discreteness arises from the fact that Schrodinger's Equation is a differential equation, and confining a particle means imposing conditions on the "fence" surrounding it. In the mathematics of differential equations, these so-called "boundary conditions" create a discrete family of solutions which can be numbered 1, 2, 3, etc (but cannot take values in between!). The main takeaway of this point is that confined particles (like atoms in an electromagnetic trap) have energies that take on discrete values like a ladder, and most importantly, that this "ladder" has a bottom rung, the ground-state energy.

The next thing to know is that quantum mechanics, for deep and mysterious reasons, classifies particles as either fermions or bosons. Fermions (which include elementary subatomic particles like electrons and quarks) obey something called the Pauli exclusion principle, which states that identical fermions cannot occupy the same state (i.e. share exactly the same properties like energy, position, etc). One of the main results of this principle is the creation of electron orbitals in an atom, where different electrons in a multi-electron atom "stack up" in energy in such a way that only the outer "valence" electrons participate in chemistry, and the inner electrons are effectively ignored. Without Pauli exclusion, all the electrons would want to collapse into the lowest orbital, and chemistry would not work. However, there is another class of particles called "bosons," which do not obey Pauli exclusion. Bosons are perfectly happy to cluster in the same quantum state. The category of bosons include photons (light), and any composite particle made up of an even number of elementary particles (e.g. a helium-4 atom, which has 2 protons, 2 neutrons, and 2 electrons).

The Pauli exclusion behavior is not immediately obvious to us in daily life. We certainly do not sort the things we encounter as bosons or fermions. The distinction between bosons and fermions is only really clear at low temperatures. For most macroscopic collections of identical particles at room temperature (like oxygen molecules in the air, or the water molecules in a glass), the "ladder" of energy is pretty spread out: there are so many available rungs that the energy spectrum almost looks like a ramp, and more importantly, there are so many available rungs that all the particles can occupy different ones. Technically speaking, temperature is a measure of the average energy of the particles. At room temperature, the occupation of different energy levels is like a bell curve (or another bell-curve-like distribution, namely the Maxwell-Boltzmann distribution), and temperature says where the center of the curve is located. At low temperatures, however, fewer particles are longer energetic enough to occupy higher energy levels, so the lowest energy levels get more and more occupied. At this point, the Pauli exclusion principle kicks in. Fermions refuse to crowd together, and at the lowest temperatures, the lowest energy levels are each occupied by a single fermion (this is actually a pretty good description of electrons in metals at room temperature; the characteristic temperature scale for this "Fermi gas" behavior is actually higher than most metals' melting points!). Bosons instead all fall into the lowest energy level, the ground state energy. This is the phenomenon of Bose-Einstein condensation; a bell curve no longer suffices to describe the occupation of different energy levels, since there is now a giant spike in the distribution corresponding to ground state occupation. The transition to Bose-Einstein condensate is an example of a quantum phase transition, a quantum version of water freezing into ice, or an iron bar becoming a permanent magnet.

That's my understanding of Bose-Einstein condensation, which is very much a thermodynamic description: a picture of many, many particles undergoing a phase transition. Note that the particles do not change their identities or even their chemical properties, in much the same way that individual water molecules do not change their properties by freezing into crystalline ice. Liquid water and ice are distinguished not by chemical makeup, but by collective, macroscopic properties like density, temperature, and the presence or absence of crystalline structure. Likewise, the effect of Bose-Einstein condensation is instead a collective phenomenon; phase transitions describe collective behavior. As a side note, the mathematical description of Bose-Einstein condensation has been used to explain both superconductivity and superfluidity.

Now I will explain the weak force. Quantum field theory (QFT) is not my specialty, but I think I have learned enough to describe the basics. QFT is more the realm of particle physicists, and the massive energies required to conduct particle collider experiments (at, say, the LHC) mean their description of fundamental physics needs to include special relativity, the branch of physics governing what happens when matter starts going close to the speed of light and when the concepts of space and time start acting funky as a result. Particles can thus be described as little wave-like excitations in a universe-wide collection of "fields"; all electrons, for example, are truly identical, as they are just waves in the same "electron field."

All the elementary building blocks of matter (quarks and leptons) are fermionic particles. All the four fundamental forces (it's maybe more accurate to call them types of interactions between different matter particles) are mediated (or "carried") by bosons. The word "mediated" is a bit awkward, I admit. The idea is that we reduce our description of "interaction" to the most basic possible picture: a matter particle (say, an electron) emits a force-carrying boson that is then absorbed by a second matter particle. For example, the boson that mediates the electromagnetic interaction is the photon. It is no mistake that light, being made of electromagnetic waves, is also described by packets of photons. Any matter particle with charge can emit or absorb a photon.

Photons are massless and therefore travel at the speed of light; as a result, the electromagnetic interaction between charged particles occurs at the speed of light. Using some very complicated matrix mathematics, you can derive Maxwell’s Equations, and consequently all of electromagnetism, from the QFT description of photons and electrons.

The weak force gets three bosons, called the W^+, the W^-, and Z^0. Unlike the massless photon, these bosons have mass, meaning a certain amount of energy needs to be pumped in (via $E = mc^2$) to create these bosons from nothing (i.e. from occupation = 0 to occupation = 1), on top of whatever kinetic energy the bosons need to move around. The two W bosons are charged, while the Z is not.

One more quick side note: the W and Z bosons are not “visible” to our eyes in the same way that photons are. Our eyes contain molecules that react to photons (and not even all of them, just those with wavelength 400-700nm), but that’s it – no other fundamental bosons. Our understanding of photons isn’t even direct – we observe photons indirectly through their effect on matter (the photo-sensitive molecules in our eyes). Similarly, our only understanding of the W or Z bosons has to come indirectly from special detectors that we build for finding neutrinos or measuring radioactive decay, which produces matter particles like the alpha particle in alpha decay and electrons in beta decay, or photons in the case of gamma decay.

The following diagram illustrates the standard example of the weak interaction: beta decay. A neutron, comprised of one “up” quark (charge +2/3) and two “down” quarks (charge -1/3) becomes a proton (two up quarks and one down) when one down quark becomes an up quark by emitting a W^- boson. This W- boson in turn creates an electron and an anti-neutrino (its arrow is backwards because it’s actually antimatter).

The weak force happens on such small length scales (within an atomic nucleus) that we basically cannot isolate the W and Z bosons, even in our detectors; we can only observe its effects, like the emission of electrons in beta decay. Even when we collect enough radioactive particles to observe the effects of the weak force in the aggregate, the statistics are Poissonian – a probability distribution of random events very different from the statistics that govern thermodynamic quantities.

In conclusion, Bose-Einstein Condensation and the weak interaction are not really related. The mathematical formulation for one does not really apply to the other. It’s intriguing to think of the connection, but once you think about it and try to tease out the connections, you conclude that there aren’t really that many connections. The only connection I could think of is called “spontaneous symmetry breaking,” which shows up in the descriptions of both superfluids and the Standard Model of particles (specifically the theory governing the Higgs boson as well as the so-called electroweak force, the unification of electromagnetism with the weak force). This is a very cool topic that’s quite prominent in today’s research in both quantum field theory and condensed matter (the study of electrons in solids, encompassing superconductivity and superfluidity).