Supernova type II – the neutrino theory

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End of the life of a big star, known facts

- The most of the lighter nuclear fuel has gone, none of such kind is left in the core, but in the outer layers of the star certain nuclear processes are still going on producing nuclei of lighter elements.

- The most of the energy and the pressure that prevents the star from collapsing comes from the inner core. The pressure in the later stages of a stars life is produced predominantly by neutrinos from the nuclear processes in the core (in the earlier stages it was mostly by photons).

- In the core there is mostly silicon (Si), when the last stage begins. Fusion of silicon produces iron (Fe) and Nickel (Ni) and other nuclei of about same size, but in most part iron is produced. The core, and the whole star, is electrically neutral: there are not only nuclei, there are electrons as well, but it is all in form of pressurized plasma rather than atoms.

- The last fusion stage takes about two days. Then there is no more energy to win from fusion. The core energy production stops, the outward pressure is gone, and the star begins to collapse under its own gravitation.

- Huge amounts of gravitational potential energy is released, which heats up the core so that earlier impossible reactions suddenly can occur. This takes a few hours. The time is too short for the outer layers of the star to participate, the core processes dominate.

- The collapse stops if the core size is under a certain limit. The stop is caused by degeneration pressure from neutrons that will form when electrons react with protons due to weak interaction (which is considerably strong in these circumstances of an extreme pressure and temperature).

The dying star becomes a supernova, theories why

It is generally accepted that the process producing the outward shock-wave is not fully understood in all detail yet. In my opinion the crucial part is the neutrino process.

✗ The supernova explosion is often described as an outward rebound of in-falling matter. Such a theory takes the center of core as some kind of solid. Matter falling against it bounces back causing the rebound shock. It is a classical kick-back idea of an environment that is very long away from what are valid prerequisites for classical physics. Most certainly it is wrong.

> *- There are many theories of such a shock-wave, but none has turned out to be fully satisfactory. The point is that the core is not really solid, nor has it settled in neutrino star state yet. The energy per particle is still too high them to settle in a degenerate neutron-star energy state. Some process must first bring out the extra energy. No kick-*

back process is really possible because the process order is wrong. First the extra kinetic energy must out, only then can there be a solid core. In stead the core is still in a high energy high pressure plasma state.

- All reactions in there are of course basically quantum mechanical, numerous different reactions and combinations of them, which can not be easily investigated in detail. Still, it might be realistic to consider the core as pure plasma with zero elasticity. It can not be expected to support any shock waves, and the energy and the momentum of the collapse only increases the core temperature and causes no rebound shock.

- The temperature-induced random kinetic energy of core particles increases during the collapse, but medium free flight path for a heavy particle in the dense star core is less than a nuclear dimension. Interactions between particles with the strong and electromagnetic forces involve high-energy processes with many massive particles, and further randomize the flight directions, not allowing the particles to fly persistently outward. Not even this is a way to them to escape from the gravitation of the star.

- If nothings comes on the way, the inward going particles, theoretically, could pass the center of the star and continue out. Most particles have mass and are gravitation bound. If they loose kinetic energy in collisions, as most particles do, they are still gravitation bound and can not leave the star. If there are particles that gain kinetic energy in the star core processes, those might escape. Neutrinos are such particles, and a vast amount of them have seen to leave the star, in fact. The other particles that also in fact fly off are secondary, as will be seen below, a rip off from outer parts of the star by the extremely dense outbound neutrino front.

- The conclusion is: any kind of rebound shock wave from the collapse is certainly not what is causing the supernova type II explosion.

- The most interesting, and probably dominating, outward flow is from neutrinos from the electron capture process.

    - Neutrinos, as they have a low reaction rate, do not generate a sharp shock-wave, it is more like a rapid flow. It fits well to what is seen from known supernovas: the explosion takes several hours.

    - Although neutrinos are in some extent recaptured in the high density plasma, reversing in some part the electron capture reaction, the electron capture will repeat and win in long run, and it ends up with a tremendous flow of free neutrinos.

    - These neutrinos are originally flying in all directions, also toward central parts of the core. But nothing preventing them from passing trough the center also these neutrinos become in end outward directed. Due to their long medium reaction time plenty of the neutrinos will in end reach the outer rim of the core, and all of them have their momentum direction outward.

    - Neutrinos are created as electron neutrinos, but neutrino oscillation makes a big part of the original neutrinos to behave like mu and tau neutrinos part of the time. These other neutrino flavors have a lower probability in reacting, because the main reverse reaction is due a capture of electron neutrinos. This notably supports the free flow of neutrinos out of the core.

- At the outer rim of the star core the neutrinos still have certain probability to react with hadrons of the core. Although only some 10% of the neutrinos react there, this is more than enough, because of the enormous number of released neutrinos. (There are as many neutrinos as there were protons, and nearly as many as there were hydrogen atoms originally forming the star core.)

- The kinetic energy of the outward directed high energy neutrinos is thus in some part transformed into outward flow of hadron particles. The velocity of these hadron particles is now mainly outward directed and exceeds the escape velocity, thus over-winning the pull of gravitation, and throwing the particles out of the star.

- About 10% of the neutrinos are calculated to react, and they are about as many as core hadrons. On the other hand it is known that about 10% of the mass of the star core is thrown out. Those figures in deed do match!

◆ The star now explodes as a supernova, the outer parts are thrown out. The flying neutrinos and explosion take with them the excess energy, the star core cools down and settles as a neutron star. The explosion energy comes originally from the released gravitational energy, and is momentarily as much as all the energy produced by all (normal) stars together in a whole galaxy.

Note: This provided the star was heavier than Chandrasekhar limit. Lighter stars do support the electron capture and then do not explode as supernovas, but cool down slowly and become white dwarfs. For heaviest rest core sizes, more than Tolman-Oppenheimer-Volkoff limit, there is no stop of the core collapse after the supernova explosion: a black hole will be formed.

◆ <u>It is important to note that the low reaction rate of the neutrinos is essential for the process at all to be possible</u>. If they had higher reaction rate they would only increase the inner pressure of the core but were not able to torn it off. They must react late in order to reach the outer rim of the core. <u>Supernova explosion is then basically caused by the weak interaction</u>. The weakest force gains here the strongest power!

A sketch of the core neutrino processes

➔ The core of the star will collapse from size of about 1000 km to a size of 100 km, to a 1000-fold density. The gravitational energy released is something about 10^{44} J (?). This energy is plunged into new reactions.

➔ In the core plasma there are nucleons and electrons. Nucleons are at first both protons and neutrons in about half and half. Protons will now participate in a process called electron capture.

- *Nucleons consist of u ("up") and d ("down") quarks. A proton is made of the quark combination u-u-d, a neutron is made of combination u-d-d. The quarks do not directly react with electrons, so an additive process is needed for the capturing of an electron.*

- *The quarks involve different fields, in fact all of the four basic fields that seem to exist in nature. The gravitation field, the electromagnetic field, the strong nuclear field (often called color field), and the weak nuclear field. These three later (but not gravitation, as far as we know to day) can be described as quantum fields, where the field is formed by virtual (very short lived) processes involving a field particle, a field boson.*

1. *The electromagnetic field is coupled to the charge, u-quark has charge* $+2/3$ *, and a d-quark* $-1/3$ *. Thus a proton has total charge* $+2/3+2/3-1/3=+1$ *, and a neutron* $+2/3-1/3-1/3=0$ *. The electromagnetic field boson is the photon, the particle of light and electromagnetic radiation. There is only one kind of field coupling, that to the electric charge (magnetic coupling comes from charge together with angular momentum).*

2. *The strong nuclear field (color field) bonds the quarks together in the nucleons. It is of the greatest interest in the forming of the nuclei of the chemical elements. The strong field bosons are called gluons. There are three charges called "colors", and three corresponding "anti-colors". There are eight different kind of gluons, every one carrying a "color"-charge pair, one "color" and one "anti-color".*

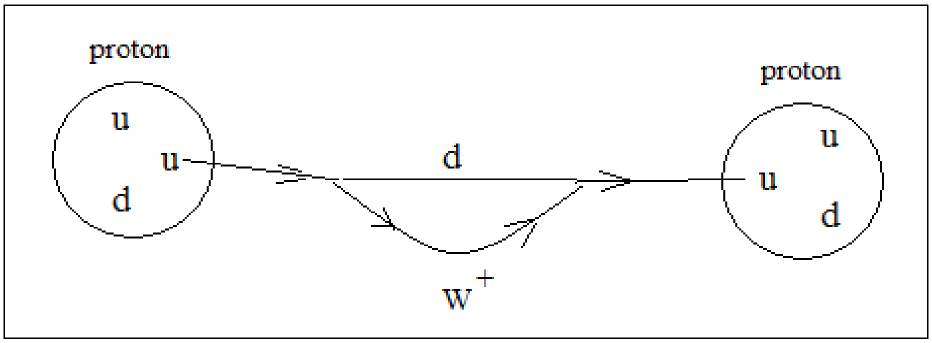
3. *The weak field is more similar to the electromagnetic, except that there are more than one field boson, in fact three, positively charged* W^+ *and negatively charged* W^- *, and the electrically neutral* Z *. Correspondingly there are different virtual field processes. Here below explained in more detail the one involving the positive weak boson.*

There are plenty of particle processes going on in the hot core, but very few of them are able to change the particles to anything else than they are. The protons, neutrons and electrons fly furiously back and forth mainly under interactions caused by two forces, the strong nuclear force, and the electromagnetic force. The result is increasing velocity, pressure and temperature. The quarks and electrons mix up but electrons do not directly react with the quarks, except bouncing by electromagnetic forces. Quarks are by their nature confined to a volume of nucleon size, 10^{-15} meters. At the end the medium free flying path for an electron is not longer than that. Which also means that there is no way for energy to come out than via convection, which is slow, and thus gravity is able to control the star as a whole.

The process that triggers the supernova explosion is the weakest of the forces. (Gravity is weaker calculated per particle, but in total it is now the strongest force.) And it turns out that the weakness is the key, because all the stronger forces become confined. Strong reactions mean rapid reactions, which then have time only to affect a very tiny environment, unable break the overall balance between the temperature, pressure, and gravitation, the conditions that controls the star at large scale. Weakness is the key because it becomes a strength in large scale. Weak forces react too slowly to be eliminated in the small scale processes, which is the fate of the stronger forces. Neutrino reactions are weak per particle, which gives them time to gather strength so that they, appearing together in large amounts, can temporarily win over gravitation and cause the star to explode.

I describe below the weak process that in end will do the trick.

- A virtual process, the process is very short lived: $u \rightarrow d + W^+ \rightarrow u$. The u-quark emits a positive weak boson, changes to a d-quark, which immediately absorbs the boson and changes back to the u-quark. It is only a feeble fluctuation and does not change the quark, or the proton, permanently. According to quantum field theories such virtual processes create the force fields. The weak bosons are responsible for creating the weak nuclear field, which, as the name reveals, is a very weak force.

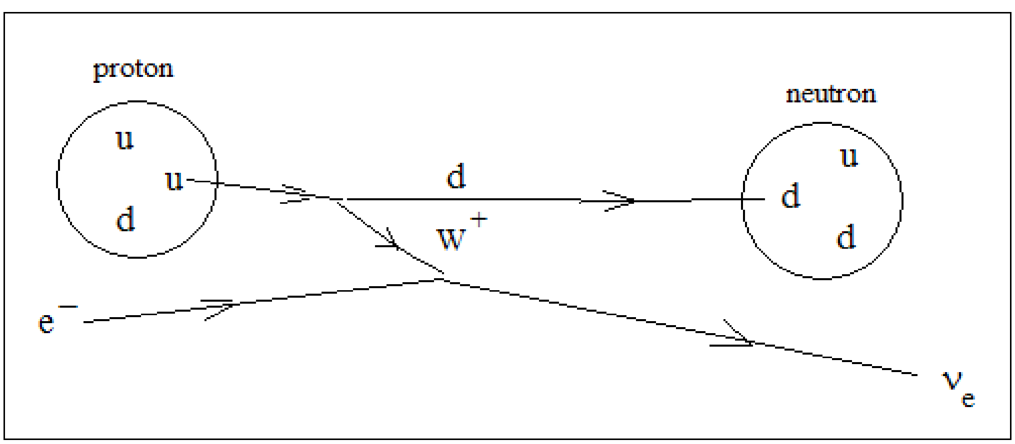


- An electron can react with the weak boson only if it is "very near", which it hardly never is in normal circumstances. But in the compressed core of the dying star this weak nuclear reaction becomes possible. Electrons are much lighter than nucleons and thus gain much larger velocities As a result the electrons plunge down amongst the quarks inside the protons more and more often, which increases greatly their probability to react with the virtual bosons of the weak force field.

- Electron capture in a weak process:

$$u \rightarrow d + W^+$$

$$e^- + W^+ \rightarrow \nu_e$$



Note: There might come out photons too (?), but here in the star core photons have such a short life paths before becoming absorbed that we can in all occasions ignore them.

- The virtual d-quark is now "left alone" without the virtual weak field boson. In effect the u-quark has been changed to a d-quark, and an electron e^- to the electron-neutrino ν_e . This kind of processes become very effective in the compressed core, changing nearly all the available protons to neutrons, and all electrons to neutrinos. Neutrinos are neutral, not repelled or attracted by anything, and react only weakly (by the weak field) with other particles. Even here in the extreme density they have a relatively low reaction rate and will at end escape the scene. This whole process of converting all protons to neutrons, and releasing a huge amount of neutrinos, takes only a fraction of a second, but then flying further across the whole star may take hours.

- Neutrinos have very low mass (practically zero compared with the other particles). They escape with (nearly) the velocity of light. In collision processes generally, it can be shown, the lighter particle gets the major part of the momentum and the kinetic energy. The neutrinos now carry off a big part of the kinetic energy of the star core particles.

- When losing energy to the neutrinos the core experiences a rapid cooling. Generally in case of gravitation this leads to lower pressure, the system shrinks and gains more gravitation potential, and will in end be even hotter than before. In this case there is a quantum mechanical barrier: after the neutrons have gone down to their lowest energy states their spatial distributions ("neutron orbitals") are fixed by the strong interaction, which in this case is stronger than gravitation. There is no more compression, and the innermost part of the core settles down as a neutron star.

  Note: If the core is heavy enough, then not even the strong interaction can halt the compression. There is then, as far as is known, no stop any more, and the core collapses to a single point, a "singularity". It then has an infinite density but limited mass, the mass is still the same as that of the collapsing core. It also means that the star has become a black hole. It might be that the "singularity" inside the black hole is a mathematical artifact only, but nobody really knows. A mathematical point is of zero-extension, but already the distances just before are so short, so that what really happens should be explained by a quantum theory. Unfortunately, there is still no decently working quantum theory of gravitation.

- The neutrinos fly off, only some about 10% of them will react with other particles, when flying through the entire huge mass of the star core. That means that also neutrinos starting towards the center of the star will in most part fly through it and end up in the outer rim of the core on the other side before they (possibly) react with other particles. The most of the reactions then will occur with outward flying neutrinos, which generates an outward shock wave.

- Even if the reacting neutrinos are in minority the energy given to the shock wave is large enough blasting away the outer part of the core. It takes with it all the outer parts of the star, forming a blast nebulosity (like that in the well known Crab nebula). Computer simulations have shown that the random pattern created when the neutrinos blast off the outer part of the core will nearly keep its form, and only be magnified in size during the rest of the supernova explosion.

- The elements created in the processes in the star are spread in the space. The neutrino burst is so intense that it can be detected (despite the extremely low reaction rate of neutrinos) millions of light years away. The light intensity from a supernova during the first days is more than that from an entire galaxy with hundred billions stars. It comes almost all from the gravitational energy released in the collapse. Still it is only from a minor part of that. The most of the energy escapes with the neutrinos.

- The low reaction rate of neutrinos is crucial here. Otherwise they had reacted immediately, and then only would heat up the core but not be able to blast it out. No neutron stars would form, and no spreading out of chemical elements. One gets the odd feeling that the existence of neutrinos and the weakness of the weak interaction has a built in purpose here.

THE END