How Does a Neutron Star Remain a Stable Entity?

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An Introduction to Neutron Stars

What *are* Neutron Stars?

A Neutron Star can be thought of as the 'fossil' of a massive star. When stars hundreds of times more massive than our own die, they expel trillions of tonnes of its insides in a Supernova explosion, as the star collapses under its own weight. What remains is a *small* (relatively speaking– a Neutron Star has a radius of ~13-14km[1]) but incredibly dense sphere of iron nuclei. In fact, Neutron Stars are the densest known object in the universe beside black holes, and when Neutron Stars die, they become them. This extreme density results in the extreme forces that keep the star intact, along with the unknown properties of Neutron Stars that currently appear to break our current understanding of physics.

This report investigates the forces that keep a Neutron Star together, in the aim to discover what opposes gravity to stop the star from spontaneously collapsing. We will also discuss how the universe can even produce such an entity, and finally hypothesise what might happen if the fragile stability of Neutron Stars was to be broken.

My Initial Response to this Question

A main reason for choosing this subject to write about was that, prior to taking on this project, my thoughts as to what forces inside a Neutron Star prevented the collapse of its core were very primitive.

My initial ideas before researching were that the Strong Nuclear Force was the main upholding force operating in a Neutron Star, however I was unsure as to what role it had (due to the dual properties of this force). Regarding the forces at the core of a Neutron Star, my only prior knowledge was that the star's core is the densest location in the universe, besides the singularity of black holes. Therefore, I predicted that in the core, atoms would be squished so close together that they would all combine into a single 'atom-like' type of particle that could not be separated again. My primary aim is that, in the conclusion of

[1] = Tereza Pultarova (published 20/5/2021) – "neutron stars … have a radius of between 8.2 and 8.9 miles (13.25 and 14.25 km)." - https://www.space.com/neutron-stars-bigger-than-thought.

this report, I will be able to provide a much more comprehensive and accurate explanation for the inner mechanisms of Neutron Stars.

How can a Neutron Star be Formed?

Step 1: Kill a Supermassive Star

A supernova explosion marks the death of a supermassive star, and the birth of a Neutron Star. A stable star (such as our Sun) contains mostly Hydrogen and Helium (with ~10% of the latter), and these elements keep our star stable. The weight of the star puts immense pressure on its core which, unless it resists against gravity, will collapse into itself - forming a black hole. To combat this, Nuclear Fusion takes place:

Nuclear Fusion is the process of converting relatively light nuclei into heavier ones – releasing energy in the process. This fusion energy relieves the inward pressure of gravity - keeping the star from imploding. Currently, our star is in the process of fusing Hydrogen (along with its isotopes, Deuterium and Tritium) into Helium – a process which releases enough energy to combat the sun's weight. Though nuclear fusion requires a huge density (and hence, a huge core pressure) to operate, it single-handedly keeps our star stable, and hence gives our planet life. Through this process, the Sun fuses together millions of tonnes of hydrogen nuclei each second, and it will continue to do this for another 5bn years until its hydrogen source has been exhausted.

When this point is reached for stars much more massive than our own, there is not enough fusion energy to combat the star's weight, and thus the star begins to implode. The weight of the star crushes into its core with an insurmountable pressure, forcing heavier nuclei to fuse together in a drastic effort to keep the star stable. In response to this, the star begins to expand and turn red as heavier elements are fused together – first Helium, then Carbon, Neon, Oxygen, Silicone, and finally Iron[2], where fusion stops entirely. Iron is classified as 'Nuclear Ash', meaning it cannot be fused[3]. This is because the energy required to break up a nucleus (also known as the binding energy of a nucleus) increases as the nuclear mass increases. This occurs until we reach

[2] = Kurzgesagt (Published 10/11/2019) – "The core burns hotter and faster … fusing heavier and heavier elements. Carbon burns to Neon … to Oxygen … to Silicone … to Iron." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.
[3] = As Previous – "Iron is nuclear ash. It has no energy to give and cannot be fused."

iron-56[4], where this binding energy becomes greater than the energy we receive from fusion – as is shown in the graph below.

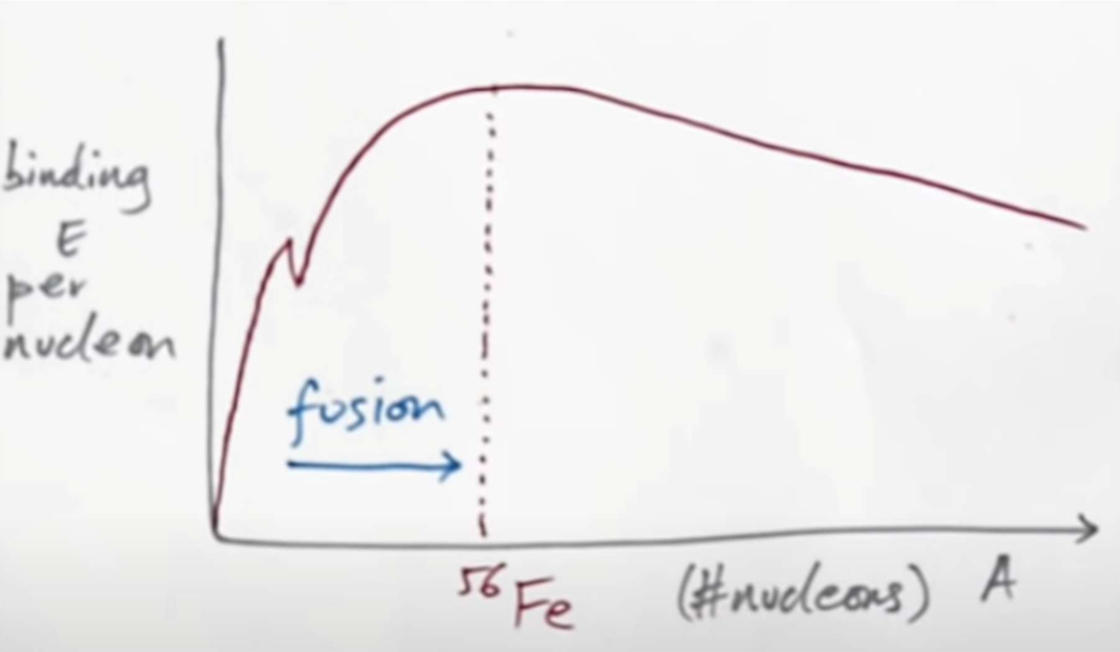

Figure 1: Graph of binding emery per nucleon. Credits: 'Science Shorts' - [*https://www.youtube.com/watch?v=b7upbQtJeno*](https://www.youtube.com/watch?v=b7upbQtJeno)

We therefore say that the reaction is endothermic[5]; as a result of this, fusing iron nuclei would not aid the star's core in combatting the immense weight, and hence fusion stops entirely. With nuclear fusion no longer acting in the star, the balance of forces is broken, and the star begins to collapse.

The 'Neutron' in Neutron Star

At 25% the speed of light, the star compresses, and crushes this newly made iron core with unbearable pressure. This pressure is so great that the iron atoms' orbital electrons are forcibly pushed into their nuclei, merging into protons to form neutrons[6] (as the negative charge of an electron cancels out with the positive charge of the proton) – turning the iron core into a 'clump' of neutrons that are squeezed together by gravity. This process is called electron capture:

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[4] = John J. Cowan & Friedrich-Karl Theilemann (Published 10/2004) – "The binding energy per nucleon increases with nuclear mass only up to iron-56." - https://physicstoday.scitation.org/doi/10.1063/1.1825268.
[5] = As Previous – "The production of any heavier nuclear by direct fusion is endothermic." - https://physicstoday.scitation.org/doi/10.1063/1.1825268.
[6] = Kurzgesagt (Published 10/11/2019) – "Gravity [pulls] the outer layers in at 25% the speed of light.", "The pressure of the collapsing star is so great that electrons and protons are fused into neutrons." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.

Electron capture is the process in which an atom's nuclei 'captures' one of its electrons from the ground state and pulls it into a proton. The two particles exchange a charged W boson, and then react with the formula $p + e^- \rightarrow n + Ve$, where Ve = electron neutrino (a high-energy, neutral particle). This occurs in almost every proton in the iron core, releasing so many neutrinos that, in the first few seconds after a star begins collapsing, their combined energy is equal to the energy from all the light emitted by all the stars in the observable universe[7]. Photons are also released in this reaction; because an electron has been 'pulled' from the ground state, a gap has been formed, which other electrons fill due to entropy. This movement of electrons releases photons as they cascade down the atom's energy levels.
Electron capture typically occurs in an atom that has too many protons and not enough neutrons, however this is not necessarily the case during the collapse of a star – the high pressure of the implosion *forces* electron capture to occur.

Returning to the star, the star's weight implodes onto the core, then rebounds as a powerful shockwave - a supernova, the light of which will outshine entire galaxies[8]. This explosion also results in heavy elements such as Silver & Copper to be produced, which are catapulted outwards to the universe.

During the rebound of the star's implosion, one of two events can occur here depending on the mass of the star:

1) If the mass of the star is large enough (and therefore its implosion's strength is strong enough) to overpower the upholding forces in the core, the core collapses into a black hole.
2) If the mass of the star is not large enough (and therefore its implosion's strength is not strong enough) to overpower the upholding forces in the core, the core remains after the supernova as a Neutron Star.

An interesting question arises here: without nuclear fusion taking place when the star collapses, how can the iron nuclei withstand the

[7] = Ali Sundermier (Published 29/7/2017) – "In just the first few seconds after a star begins its transformation into a neutron star, the energy leaving in neutrinos is equal to the total amount of light emitted by all of the stars in the observable universe." - https://www.symmetrymagazine.org/article/five-extreme-facts-about-neutron-stars.
[8] = Kurzgesagt (Published 10/11/2019) – "This is what we called a Supernova explosion, and it will outshine entire galaxies." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.

immense force of gravity? This brings us to the main topic of discussion for this repot – the upholding forces of a Neutron Star…

Preventing the Collapse of a Star - The Neutron Star's Upholding Forces

The Strong Nuclear Force

The Strong Nuclear Force (abbreviated to SNF) is one of the four fundamental forces in the universe (alongside the Weak Nuclear Force, the Electromagnetic Force, and gravity). The role of the SNF is to pull nucleons (protons & neutrons) together to form the nucleus of an atom. What makes this force so key for Neutron Stars, however, is that it contains a dual-purpose – if the SNF was only attractive then all the nucleons in the atom would merge, but if it was only repulsive then nucleons wouldn't combine to form nuclei. The solution to this is that the SNF is **both positive and negative**, depending on how far the nucleons are from each other. If we plot the graph of this, we get the following:

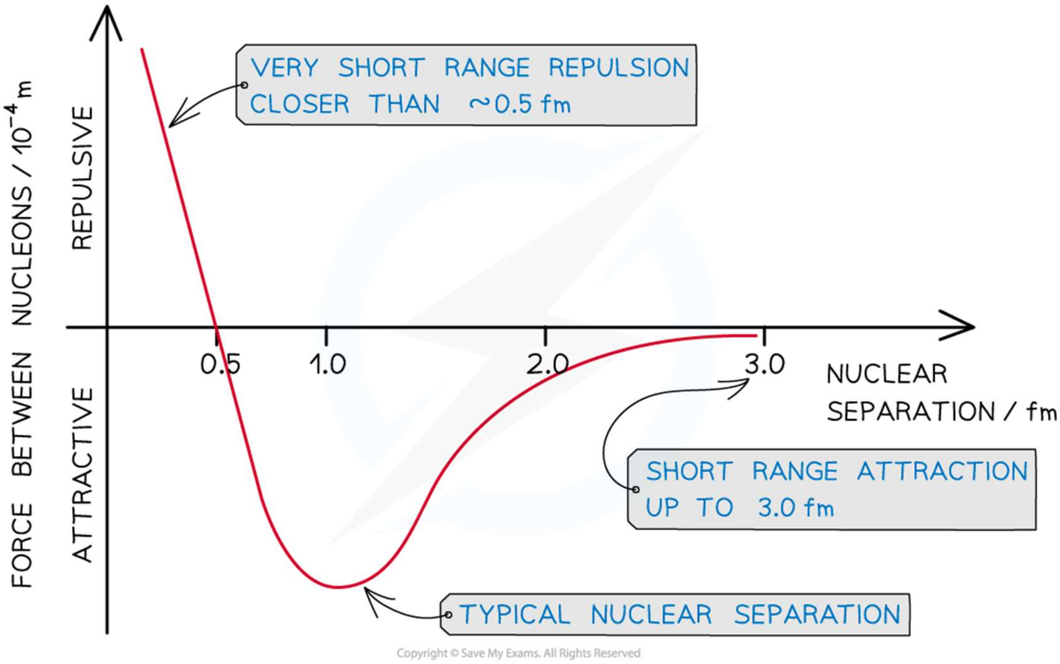

Figure 2: Force-Distance graph of SNF. All picture credits go to savemyexams.co.uk

Thus, if we place two nucleons at a relative distance of 2fm and observe their movement, they would begin to attract to each other, then become close though that they repel (under 0.5fm), then become so far apart that they could attract again, etc. Over time, these two nucleons would settle at ~1fm apart from each other, where they have the greatest entropy.

And hence, we have found a potential upholding force for the Neutron Star: as the star's core is pressed upon during its collapse, the core's nucleons would be forced incredibly close together, so close that they would be <0.5fm apart and would therefore repel - pushing against the star's weight.

Alas, the SNF cannot be the only force at play here; on its own, it simply isn't powerful enough. It is predicted that this force can uphold a star's core with mass 1.8 * that of the sun, however the typical size of a Neutron Star can be upwards of 2.5 times![9] So we can therefore deduce that there must be another force that combines with the Strong Nuclear Force, which transpires to be Neutron Degeneracy Pressure – a mechanism directly resulting from the Pauli Exclusion Principle.

An Introduction to the Pauli Exclusion Principle

The Pauli Exclusion Principle is best explained when discussing electrons in the shells of atoms, but the information holds true for the neutrons in a Neutron Star. In a nutshell, it states that no two fermions (such as protons, neutrons & electrons) can occupy the same quantum space[10].

Fermions are 'indistinguishable' particles, meaning that if two or more fermions have the same properties (such as mass, charge, etc) then it is impossible to tell the two apart[11]. We can combine all the properties of an electron into a single mathematical function called its 'Wave Function' (denoted with Ψ), and by squaring the modulus of this function (to get $|\Psi|^2$), we can discover information such as "how likely am I to find this electron in position X vs position Y?"[12]. The important thing to note about a system's square modulus wave function, however, is that we can directly measure it, and because of this the following method applies...

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[9] = Michel van Biezen (Published 10/4/2020) – "some calculations were done and it was estimated that [neutron degeneracy pressure] can only account for upholding a mass of a neutron star [with] ... 0.7 times the mass of the Sun, and we know that the mass of a neutron star falls ... between 1 and 2.5 times the mass of the Sun." (2.5 - 0.7 = 1.8 as NDP is the only other force at play) - https://www.youtube.com/watch?v=G5EjC7x8Egs.
[10] = Parth G (Published 27/4/21) – "this is a principle that says no two fermions can occupy the same quantum state" - https://www.youtube.com/watch?v=INYZy6_HaQE&t=535s.
[11] = As Previous – "fermions are a type of indistinguishable particle, which means that two fermions of the same kind cannot be told apart from each".
[12] = As Previous – "its wave function [is] ... a mathematical function that contains all the information we know about that system. ... its square modulus ... gives us information like 'how likely we are to find the system in a particular location in space'?".

As fermions are indistinguishable particles, we can say that the $|\Psi|^2$ of a system with electron A at location X, and electron B at location Y, has to be identical to the $|\Psi|^2$ of another system where electrons A & B have swapped places (electron A at Y, electron B at X), as if the $|\Psi|^2$ was different then we would be able to measure it[13]. Using standard mathematical notation, this gives us the equation $|\Psi_{(A,B)}|^2 = |\Psi_{(B,A)}|^2$. By taking the square root of both sides, we get two equations: $\Psi_{(A,B)} = +\Psi_{(B,A)}$ (where the wave function becomes identical under particle exchange), and $\Psi_{(A,B)} = -\Psi_{(B,A)}$ (where the wave function becomes negative under particle exchange)[14]. These different equations represent different sets of particles - the $+\Psi_{(B,A)}$ equation refers to particles called bosons, and the $-\Psi_{(B,A)}$ equation refers to the particles of interest for this discussion, fermions[15].

With this in mind, we can apply our fermionic equation [$\Psi_{(A,B)} = -\Psi_{(B,A)}$] to atoms. If we have two orbital electrons in an atom, each with the same square modulus wave function, their normal wave functions must oppose. This means that, when we observe the system (which, under the laws of quantum mechanics, collapses the system's wave function), the location of electron A must oppose that of electron B, and therefore we will find the electrons in **different energy levels** / electron shells[16]. This fulfils the Pauli Exclusion Principle, as the two electrons (being indistinguishable fermions and therefore having the same wave function) cannot share the same quantum state, so we must find them in different locations in space.

One subtle oversimplification to clarify in this explanation is the assumption that, because fermions are indistinguishable, they must have identical wave functions. The issue here is that we cannot always assume that this results in the electrons being in different electron shells; after all, a typical atom can have dozens of electrons in each shell. This links back to my previous definition of a wave function, being a representation of all a system's (or in this case, an electron's) properties – if two or more electrons have the same wave function then they cannot be in the same quantum state (thus Pauli Exclusion

[13] = Parth G (Published 27/4/2021) – "the square modulus of ... our wave function when the system is in orientation AB must be equal to the square modulus of the wave function when the system is in the orientation BA." - https://www.youtube.com/watch?v=INYZy6_HaQE&t=535s.
[14] = As Previous – "the wave function can be identical under particle exchange [+psi] or it can become negative under particle exchange [-psi]".
[15] = As Previous – "these conditions are referring to two different types of particle, the first case is ... a boson, and the second case is ... a fermion".
[16] = As Previous – "when we make a measurement on the system, we will ... find one electron in [one] energy level and the other in [the other] energy level".

Principle), however each electron can possess one of many wave functions depending on its properties. For the example of electrons in shells, wave functions can be influenced by the following properties[17]:

a) The shell that the electron is in.
b) The spin of the electron - in this case, either spin up (+1/2) or spin down (-1/2).
c) The electron's angular momentum.
d) The electron's magnetic quantum number.

Therefore, an electron's quantum state is defined by the above properties, along with its location, so if two or more electrons share all these properties, then they cannot occupy the same space / energy level in the atom.

This defines the basics of the Pauli Exclusion Principle, and with it we can discuss its influence in Neutron Stars due to Neutron Degeneracy Pressure.

Neutron Degeneracy Pressure

Neutron Degeneracy Pressure (NDP) is the secondary force combatting the weight of the star during its collapse. To get a sense for its strength, we'll hypothetically bring a tablespoon of Neutron Star matter to earth. If this were to happen, the immense pressure of NDP (now with the absence of gravity compressing it) would result in the matter expanding rapidly, causing in an explosion more powerful than humanity's biggest nuclear weapon, and vaporizing a huge chunk of our planet[18].

As previously stated, NDP is a direct consequence of the Pauli Exclusion Principle – neutrons (similarly to electrons) are fermions, so this principle applies in Neutron Stars when its star collapses. We can therefore say that two neutrons with the same quantum state cannot occupy the same space[19] – the only notable difference is that neutrons have different properties to electrons that form their wave functions.

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[17] = Kevin Boudreaux – "Principle Quantum Number, … Angular Momentum, … Magnetic Quantum Number, … Spin Quantum Number" - https://www.angelo.edu/faculty/kboudrea/general/quantum_numbers/Quantum_Numbers.htm.
[18] = Caroline Adams (Published 28/8/2018) – "When we bring our spoonful of neutron star to Earth, … what's inside expands very rapidly. … [It] would cause a giant explosion, and it would probably vaporize a good chunk of our planet with it." - https://astronomy.com/magazine/ask-astro/2018/08/neutron-star-brought-to-earth.
[19] = Michel Van Biezen (Published 10/4/2020) – "… so two neutrons with the very same quantum state cannot occupy the same space." - https://www.youtube.com/watch?v=G5EjC7x8Egs.

Therefore, if we try to force similar neutrons together, they will resist; this 'resistance' causes an outward pressure which helps prevent the star from collapsing and dying. Note that we are not considering the effect of the Pauli Exclusion Principle with electrons - in fact, electrons have a negligible effect on halting core collapse. This is due to the extreme heat of the star's core – because of this, all the electrons in their atom have been ionised, and therefore there are negligibly few orbital electrons in a supernova. Hence, we cannot use part (a) of the properties that make up an electron's wave function (what shell an electron is in), and thus we can discount Pauli Exclusion Principle for electrons in this circumstance.

Using calculations, scientists have calculated that Neutron Degeneracy Pressure can uphold a Neutron Star with a mass of 0.7 * that of the sun[20], and hence this force must combine with the Strong Nuclear Force to halt the collapse of a star's core – bringing the total mass of a Neutron Star that can be successfully upheld to ~2.5 * our sun. If the core of a supermassive star has any more mass than that threshold, then these two forces will not be able to stop the core from collapsing.

Ferromagnetism

The final potential force I would like to discuss is ferromagnetism, as during my research I initially believed it to be a force acting with gravity during the collapse of a supermassive star's core.

Ferromagnetism is a phenomenon in which uncharged materials (such as the iron found in a Neutron Star's core) becomes magnetised, strongly attracting itself. Ferromagnetic materials exhibit what is known as 'long-range ordering' at the atomic level, which results in the *spin* of electrons to align with each other, producing a localised yet strong magnet - what causes this 'long-range ordering' is unknown, yet physicists believe that it results from a quantum mechanical interaction[21]. However, as the directions of all these magnetic moments in all the iron atoms are un-aligned, they all act in different directions and negate each other – creating a zero-net force.

[20] = Michel Van Biezen (Published 10/4/2020) – "it was estimated that [neutron degeneracy pressure] can only account for upholding a mass of a neutron star [with] … 0.7 times the mass of the Sun." - https://www.youtube.com/watch?v=G5EjC7x8Egs.
[21] = Rod Nave – "Ferromagnetic materials exhibit a long-range ordering phenomenon at the atomic level which causes the unpaired electron spins to line up parallel with each other. … The long-range order … arises from a quantum mechanical interaction" - http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/ferro.html.

However, if the material is exposed to a small magnetic field, these fields can line up will each other, resulting in all neutrons' magnetic moments to reinforce each other, hence making the material magnetised. Once this happens, the magnetic field that made the material magnetised is amplified by up to five thousand times[22] – creating a powerful, reinforced force. In the collapse of a supermassive star (especially those that are rotating), simulations have demonstrated that the magnetic field produced can reach a million, billion times that of Earth's[23], so combined with the reinforced strength resulting from ferromagnetism, there should *hypothetically* be an incredibly powerful force that aids gravity in collapsing the star's core.

Alas, ferromagnetism has an almost negligible effect on the collapse of a star – if we take a ferromagnetic material and heat it to extreme temperatures, its 'long-range order' disappears. This point is known as the Curie Temperature, and its value for iron-56 (the element Neutron Stars are comprised of) is 1043K[24]. For scale, the average temperature of a Neutron Star is around **600,000K**, and this temperature can reach as high as 1,000,000,000,000K (1tn) when a Neutron Star is first being formed[25]. Therefore, we can definitively confirm that, due to the Curie Temperature, ferromagnetism is **not** a prominent force in the collapse of stars. Whilst magnetic moments may have a small impact on the forces acting in a Neutron Star (as ~10% of a Neutron Star is made up of charged particles), the effects of these unfortunately do not scale to the immense weight of the star.

Naturally, there are still many other forces that operate inside a Neutron Star, however these primarily operate after the star has been created. To learn about them, a look inside a Neutron Star is required...

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[22] = Rod Nave – "[An] imposed magnetic field .. can cause the magnetic domains to line up with each other and the material is said to be magnetized. The driving magnetic field will then be increased by a large factor ... , a multiplication ... by a factor of 5000!". - http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/ferro.html.
[23] = The University of California (Published 30/11/2015) – "As a rotating star collapses, the star and its attached magnetic field spin faster and faster, ... [revving] the magnetic field to a million billion times the magnetic field of Earth." - https://astronomy.com/news/2015/11/supercomputer-simulates-collapse-of-massive-stars.
[24] = Rod Nave – "For a given ferromagnetic material the long-range order abruptly disappears at a certain temperature which is called the Curie temperature for the material. The Curie temperature of iron is about 1043 K." - http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/ferro.html.
[25] = Peteris Tars – "The temperature of an average neutron star is about 600 000 Celsius. ... A newly formed neutron star can reach as high as trillion degrees Celsius." - https://universeexplained.com/how-hot-is-a-neutron-star/.

The General Structure of a Neutron Star

As we have previously mentioned, a Neutron Star can be thought of as a dense ball of neutrons (along with some protons & electrons), with a radius of ~13-14km. However, much like our own planet, we can break it down into four distinct layers – the outer crust, the inner crust, the outer core, and finally the inner core[26] (in increasing order of density, and in decreasing order of size).

Beginning with the outer crust, we find more accustomed matter: dense clumps of positive metal ions (containing protons and neutrons) with delocalised electrons flowing throughout. Even in this relatively sparsely packed layer, however, it is still hot enough for there to be no orbital electrons; they have all been ionised[27]. As we move to the inner crust, we begin to observe fewer and fewer protons, as most have merged with electrons to form neutrons via electron capture[28] – leaving whole iron nuclei made mostly of neutrons.

It's not until we reach the outer core that the Neutron Star's properties begin to change dramatically – here, neutrons (in addition with the odd proton) form what is known as a 'Fermi liquid'[29], meaning the individual iron nuclei somewhat deconfines into a dense structure called 'Nuclear Pasta', where individual nucleons are free to move without the confines of their atoms' nuclei. Within this Fermi liquid is a small number of electrons which create their own Fermi gas[30].

And finally, we reach the inner core, with properties so extreme that nucleons themselves *break down* into subatomic particles. This layer will be described more thoroughly later in this chapter.

[26] = Michel Van Biezen (Published 13/4/2022) – "4 distinct regions … the inner core, … the outer core, … the inner crust, … the outer crust." - https://www.youtube.com/watch?v=2G4u8-01Kyg.
[27] = As Previous – "We have … ions and electrons, their electrons would then be free to flow around because it would be too hot and too dense.".
[28] = Kurzgesagt (Published 10/11/2019) – "We find fewer and fewer protons, as most merged to neutrons." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.
[29] = Michel Van Biezen (Published 13/4/2022) – "It's a mixture of neutrons and protons into … a Fermi liquid, so that they're free to move around but … not separate" - https://www.youtube.com/watch?v=2G4u8-01Kyg
[30] = As Previous – "A small amount of electrons that move throughout … , that's kind of like a Fermi gas".

An Aside: Nuclear Pasta

Nuclear Pasta is thought to be the strongest known material, with a hypothesised shear modulus of 10^{30}ergs/cm^{3}![31]. It forms as we progress from the inner crust to the outer core, where nuclei become so densely packed that they begin to physically touch. Here, their internal structure rearranges to form huge cylinders and sheets, each of which containing millions of nucleons[32]. These phases are given appropriate names such as: the 'Gnocchi Phase', the 'Spaghetti Phase', and the 'Lasagne Phase'[33] (in descending order from their distances to the inner core).

Quark Pressure

Quark pressure is a force that operates inside the nucleons inside a Neutron Star, and helps keep one stable. Quark pressure was first discovered when scientists fired electrons at the insides of neutrons and tracked their motion - much like the Stanford Linear Accelerator experiment, where a beam of electrons shot at a neutron helped scientists discover the existence of quarks.

Neutrons are not in themselves fundamental particles (fundamental meaning that they are not comprised of other subatomic particles) but are instead made up of three fundamental particles called quarks, along with particles called gluons which bind quarks together. Quarks come in multiple *flavours*, but the ones found in stable matter such as protons & neutrons are the 'Up Quark' (with has a charge of +2/3) and the 'Down Quark' (which has a charge of -1/3). Therefore, due to a neutron being an uncharged particle, one must be made of an up quark + two down quarks (2/3 – 1/3 – 1/3 = 0 [neutral]). In the context of quark pressure, this means that when we fire an electron at the neutron, it will interact differently depending on where it strikes the neutron[34] (as different parts of the neutron will have different magnitudes of charge).

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[31] = M. E. Caplan, A. S. Schneider, and C. J. Horowitz (Published 24/9/2018) – "Nuclear pasta may be the strongest known material, … with a shear modulus of 10^{30}ergs/cm^{3}." - https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.132701.
[32] = Kurzgesagt (Published 10/11/2019) – "Nuclei are squeezed together so hard that they start to touch. Protons and neutrons rearranged making long cylinders or sheets - … millions of protons and neutrons shaped like spaghetti and lasagne, which physicist call Nuclear Pasta." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.
[33] = As Previous (visual)– "Gnocchi Phase, … Spaghetti Phase, … Lasagne Phase.".
[34] = Michel van Biezen (Published 12/4/2020) – "There's an interaction between the electrons and the quarks … [the electrons] get deflected depending upon where they're being hit" - https://www.youtube.com/watch?v=aDD8naA3dUg.

Due to this phenomenon, and by tracking the electrons' movement after being influenced by the neutron's quarks, the scientists discovered two pressures that act on the electrons – a repulsive pressure (that is strongest at the centre of the neutron, and gets weaker as you get further from the centre until 0.6fm, where it is negligibly strong), and a binding pressure (which is attractive, and acts from 0.6fm and beyond)[35]. These two pressures act on the quarks themselves, and hence the name Quark Pressure was given.

The two pressures (that combine to form Quark Pressure) have incredibly powerful roles inside a stable Neutron Star – the binding pressure attracts the star's neutrons together – assisting the star in maintaining its internal structure - whilst the repulsive pressure halts stable Neutron Stars from collapsing, preventing the quarks in the star's neutrons from being coming too close together[36]. This repulsive pressure is so immense, that at the centre of each neutron a pressure of ~10^{35}Pa is required to overcome it[37] – pressures only achieved by instable, dying, Neutron Stars.

The Core: Physics Breaks Down

Finally, we reach the Neutron Star's core. Scientists are still somewhat unsure as to what occurs in this layer, when matter is compressed to such an extreme, but the prevailing theory is that a Neutron Star's core is made of a 'quark-gluon plasma'.

A plasma is a type of substance where electrons do not bind to nuclei – leaving an ionised gas with a sea of negative electrons and positive ions[38]. In a Neutron Star, however, the ions are individual, deconfined quarks that can flow over one another like a liquid[39]. Due to this mechanism, along with quarks being some of the smallest particles currently known of, it is predicted that a quark-gluon plasma has the

[35] = Michel van Biezen (Published 12/4/2020) – "[Scientists] began to realize that there was … a repulsive pressure … the strongest at the centre and weaker you went further … out. By the time you got to about 6fm away … you began to have an attractive force … what we call a binding pressure." - https://www.youtube.com/watch?v=aDD8naA3dUg.
[36] = As Previous – "… A repulsive force between the quarks.".
[37] = As Previous – "[Scientists] calculated the repulsive pressure at the centre … about 10^{35}Pa, which is way bigger than the then the pressure caused by the weight … of the neutron star.".
[38] = A Professor at the University of York (3/7/2022) – "Plasmas are substances where electrons don't bind to nuclei. It's a special ionised gas with a neutral sea of negative electrons and positive ions.".
[40] = Weicheng Lv (Published 5/5/2008) – "Quarks will be deconfined, leading to a state of quark-gluon plasma." - https://guava.physics.uiuc.edu/~nigel/courses/563/Essays_2008/PDF/lv.pdf.

least viscosity-to-entropy ratio in the universe[40], meaning the particles can move over each other and flow almost effortlessly.

The quark-gluon plasma theory is predominantly supported through experiments in large particle colliders, in which physicists slam nuclei together at tremendous speeds and observe their reactions. It was detected that, as the nucleons get closer together (and therefore as their quarks get closer to each other), the force from the gluons becomes weaker[41]. However, as gluons cannot exist outside nucleons (as quarks interact by emitting gluons), the quarks instead deconfine from each other – forming a plasma of separated quarks.[42].

An analogy that supports this concept is known as the 'bag theory', whereby we can view each nucleon as a 'bag' holding quarks & gluons, with this bag representing the confines of these particles[43]. For ordinary nuclei these bags are quite far apart, however due the intense density of a Neutron Star's core, these bags can actually overlap – extending the confines of the nucleons' quarks & gluons, and allowing the particles to move freely from one bag to another[44]. This state is called a quark-gluon plasma, and in the context of a Neutron Star's core, all the bags of the nucleons will overlap to such an extent that the core itself becomes one, massive 'bag' – meaning all the quarks & gluons can flow across the entire volume.

This brings to a close our investigation as to what forces function inside a Neutron Star to keep one stable. We will now conclude this report with an exploration as to what may happen if we break the intricate balance that these forces produce – henceforth learning the possible ways that a Neutron Star can die.

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[41] = A Professor at the University of Birmingham (24/6/2022) – "QGP is hypothesised to be the least viscous-to-entropy ratio (almost perfect)".
[42] = As Previous – "To make a quark-gluon plasma, we slam nuclei together. As these nucleons get closer together, and therefore as the quarks get closer, the force from the gluons gets weaker".
[43] = As Previous – "As gluons cannot exist outside a nucleus, we can separate quarks into a plasma. ... Quarks interact by emitting gluons.".
[44] = Howard S. Matis (Published 9/8/2000) – "We can view each nucleon as a "bag" containing quarks and gluons. These quarks and gluons can move relatively freely inside their own bag, but "bag" theory says that they cannot escape from the bag." - https://www2.lbl.gov/abc/wallchart/chapters/09/0.html.
[45] = As Previous – "If we are able to produce an extremely dense gas of [nucleons] ..., then their bags can overlap. This overlap lets the quarks and gluons from different bags to mix freely.".

Breaking the Delicate Balance – The Death of a Neutron Star

Method One: Make the Star More Massive

As we previously covered, the mass of a typical Neutron Star (and hence the pressure at one's core) is not large enough to overpower the likes of the Strong Nuclear Force, Neutron Degeneracy Pressure, and Quark Pressure. However, when the star becomes more massive, the harmony between these forces can fall, resulting in the death of a Neutron Star. This is usually achieved when exceptionally large objects (such as moons, planets, and stars) collide with the Neutron Star, making its mass ~3 * that of our sun. This is roughly where the tipping point is[45] – if a Neutron Star crosses that threshold, it will begin to collapse.

When the Neutron Star's weight overcomes its upholding forces, it begins to spin – reaching a peak angular velocity of over one hundred oscillations per second. This creates the most powerful magnetic fields in the universe (100bn Tesla in magnitude - a quadrillion times stronger than Earth's)[46] – so strong, that they begin to 'pulsate', meaning they create a huge beam of radio waves in a 'pulsing-manner' every time they spin, which hurl throughout the galaxy[47]. Therefore, we call Neutron Stars in this phase 'pulsars' - the more mass a pulsar has, the faster it spins when it begins to collapse, and therefore the more electromagnetic radiation it releases in the form of pulses[48]. Consequently, as humanity is able to detect pulsars (due to their sheer power), pulsars give us an accurate method to detect Neutron Stars, along with how massive they are.

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[45] = Michel van Biezen (Published 12/4/2020) – "A neutron star is able to stay in [its] structure until … [its mass] exceeds the limit of what it can withstand - about 2.5-3 times the mass of the Sun" - https://www.youtube.com/watch?v=aDD8naA3dUg.
[46] = Kurzgesagt (Published 10/11/2019) – "When neutron stars first collapse, they … spin very fast. … This creates pulses because [of] their magnetic field. … These magnetic fields are the strongest in the Universe - a quadrillion times stronger than Earth after they're born. (Visual - 100bn Tesla)" - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.
[47] = As Previous – "This creates pulses because their magnetic field creates a beam of radio waves, which passes every time they spin".
[48] = Anton Petrov (Published 29/3/2018) - "as [pulsars] absorb matter they actually start spinning faster … and the faster a pulsar spins the more likely is going to actually release even more energy." - https://www.youtube.com/watch?v=VtcIIfXhu3Q.

One of the prominent reasons pulsars produce such an astronomical magnetic field is due to a concept called superconducting. A superconducting material is one that, by cooling it below a certain temperature (referred to as the material's critical temperature), its electrical resistivity drops to zero – making the material a perfect electrical conductor that never loses energy[49]. As Iron (the primary element in a Neutron Star) is an example of a superconductor, cooling it to almost Absolute Zero (-273.15°C) causes the remaining protons in the star's core to enter a superfluid state, hence forming a superconductor[50].

Naturally, the iron nuclei inside a Neutron Star would could never cool to its critical temperature, however it was recently discovered that superconducting materials not only have an incredibly low critical temperature, but also an incredibly high critical temperature (which is around 1–1.5bn°C - much cooler than the insides of a Neutron Star)[51]. Due to this, the iron in a pulsar's core becomes a superconductor – making its pulses as powerful as they are. However, once these immense magnetic fields eventually become subdued, the Neutron Star finally dies.

Method Two: Kilonovae Explosions

A kilonova explosion describes the event of two Neutron Stars colliding and annihilating each other[52] – occurring when two Neutron Stars become close enough to begin orbiting each other in a 'binary system'. When this happens, the stars (over millions of years) decay their orbits by emitting gravitational waves[53] – shockwaves that cascade throughout the universe - that are emitted at a cost of potential energy (which is proportional to the stars' relative distance). Therefore, as they emit more waves, their relative distances decrease, and they eventually collide. When this happens, a kilonova explosion takes place

[49] = Janet Anderson & Megal Watzke (Published 23/2/2011) – "Superfluids containing charged particles are also superconductors, meaning they act as perfect electrical conductors and never lose energy." - https://www.nasa.gov/mission_pages/chandra/news/casa2011.html.
[50] = As Previous – "the remaining protons in the star's core are in a superfluid state and, because they carry a charge, also form a superconductor".
[51] = As Previous – "In neutron stars, [superfluidity] can occur at temperatures near a billion degrees Celsius. ... This new research constrains [this] critical temperature to between one half a billion to just under a billion degrees.".
[52] = Elizabeth Howell (Published 30/8/2019) – "A "kilonova," ... - an epic explosion that likely happened when two very dense stars (called neutron stars) slammed into each other." - https://www.space.com/colliding-neutron-stars-caued-massive-kilonova-explosion.html.
[53] = Kurzgesagt (Published 10/11/2019) – "By radiating away energy as gravitational waves, ripples in space-time, [the Neutron Stars'] orbits can decay" - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.

(which, in layman's terms, can be thought of as a more powerful supernova explosion).

In a kilonova explosion, the conditions formed are so extreme that heavy nuclei begin to form again. Instead of them being formed via the nuclear fusion in stars, however, they are created from heavy neutron-rich matter becoming deconfined, then reassembling into more massive nuclei – forming elements such as Gold, Platinum, Iridium, Uranium, and more[54]. This method is currently the only known method to creating such elements, and when they are formed, they are expelled outwards into the galaxy (along with a lot of the Neutron Stars' insides). These heavy nuclei are formed though a mechanism called r-process (which stands for **r**apid neutron-capture process)[55].

A stable atom's nucleus must have an 'ideal' ratio of protons to neutrons – however, in a Neutron Star, there is a huge lack of protons (as most have formed neutrons via electron capture), so stable elements cannot exist outside of one. In extreme environments[56], however, and where there is a rich flux of neutrons[57] (such as during a kilonova explosion), r-process can occur. Here, nuclei get subjected to a blast of neutrons from the two stars colliding – giving them both a large atomic weight and an immense amount of energy[58]. These two properties make each nucleus very unstable – forcing them to conduct beta-plus decay[59], an atomic reaction where a neutron converts to a proton amongst other elementary particles (as is shown in the following formula: $n \to p + e^{+} + Ve$). This process brings the nucleus back into the valley of stability, allowing stable elements (such as those previously mentioned) to be formed in the explosion[60].

Attributable to its power, however, a kilonova explosion marks the death of its Neutron Stars; due to the immense pressure of the weight

[54] = Kurzgesagt (Published 10/11/2019) – "The conditions become so extreme that ... heavy nuclei are made again - ... heavy neutron-rich matter falling apart and reassembling. ... This is probably the origin of most of the heavy elements in the Universe like Gold, Uranium, and Platinum and dozens more (Iridium visual)." - https://www.youtube.com/watch?v=udFxKZRyQt4&t=448s.
[55] = Paul M. Sutter (Published 20/8/2021) – "R-process ... is short for rapid neutron-capture process. It happens in extreme environments." - https://www.universetoday.com/152208/astronomy-jargon-101-r-process.
[56] = As Previous – "[R-process] happens in extreme environments.".
[57] = John J. Cowan & Friedrich-Karl Theilemann (Published 10/2004) – "... ejecting a rich flux of neutrons, might be the site of the r-process." - https://physicstoday.scitation.org/doi/10.1063/1.1825268.
[58] = Paul M. Sutter (Published 20/8/2021) – "The seed nuclei get absolutely blasted with neutrons ... so that they can build up to heavier elements." - https://www.universetoday.com/152208/astronomy-jargon-101-r-process.
[59] = John J. Cowan & Friedrich-Karl Theilemann (Published 10/2004) – "[The stable nucleus] becomes unstable. Eventually, it undergoes beta decay." - https://physicstoday.scitation.org/doi/10.1063/1.1825268.
[60] = As Previous – "The unstable nuclei produced by the r-process will beta-decay back to the valley of stability to form the so-called stable r-process nuclei".

of the stars combining, their core is unable to keep the now combined star upheld. Therefore, the two stars collapse and die together.

Method Three: Angular Deceleration

This method has its similarities to Method One, however the processes on now the Neutron Star begins to collapse are quite different. In Method One we discussed that, once the Neutron Star gains enough mass to pass its threshold (~3 * the mass of our sun) then the weight on the star's core would be too much to uphold. However, a Neutron Star is able to (temporarily) pass this threshold if its parent star is spinning when it collapses.

Spinning objects, or those with an abundant of angular momentum, are more stable in nature (consider a spinning top: when you spin it, it stays incredibly steady – even withstanding large external forces – however it is only as it slows down, and begins to stop spinning, does it topple), and this fact holds true for stars. This is because angular momentum results in a centrifugal acceleration, which causes the object to accelerate away from the centre of rotation[61]. Hence, as $F = ma$ (due to Newton's 2nd law), we can deduce that a spinning star, which forms a spinning Neutron Star when it collapses, contains an extremely large centrifugal force, which makes its mass push outwardly - opposing gravity, and therefore combining with the Neutron Star's upholding forces to stop the core from collapsing[62].

As a result, a supermassive star with a core more massive than the Neutron Star mass threshold may produce a stable Neutron Star if its angular momentum is great enough. However, this Neutron Star would be unable to maintain this extreme level of spin continually; when its angular momentum decreases past a certain point, the continually lessening centrifugal force produced[63] will be overpowered by the weight of the star (which, because of the greater mass, will be even more powerful). Consequently, the star will begin to collapse in the way we saw in Method One.

[61] = Dr Christopher S. Baird (Published 15/12/2012) - "The centrifugal force … causes objects in a rotating frame of reference to accelerate away from the centre of rotation." – https://www.wtamu.edu/~cbaird/sq/2012/12/15/why-is-the-centrifugal-force-talked-about-so-much-if-its-not-real.
[62] = Anton Petrov (Published 29/3/2018) – "Some of the [Neutron Star's] external forces due to the spin are creating a centrifugal acceleration, … [which] prevents the Neutron Star from collapsing." - https://www.youtube.com/watch?v=VtcIIfXhu3Q.
[63] = As Previous – "Eventually, … [the Neutron Star] will stop spinning as fast, and as it stops spinning the centrifugal force decreases."

A Neutron Star's Death

When one of these three methods are completed, nothing can prevent the Neutron Star's death - gravity compresses the star's core so tightly that the star's upholding forces are futile against it – even the 10^{35}Pa from the neutrons' Quark Pressure. The matter in the Neutron Star's core begins to collapse under its own weight, forcing matter so close together that the core implodes, becoming a black hole[64]. A black hole is an entity with the strongest gravitational field in the world – one so powerful that even light cannot escape one. They are comprised of an event horizon surrounding an *infinitely small* point in space called the singularity, where all its mass (in this case, the remnants of our Neutron Star) is positioned.

And hence, the Neutron Star dies as the black hole draws in most of the star's matter into its singularity – leaving nothing remaining but darkness.

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[64] = Michel van Biezen (Published 12/4/2020) – "The quarks at the cell inside the neutrons at the centre of the neutron star simply cannot withstand the pressure of the weight, and ... therefore the whole Neutron Star will collapse into a black hole." - https://www.youtube.com/watch?v=aDD8naA3dUg.

Report Conclusion

A Brief Summary

In the aim to answer the question "How does a Neutron Star remain stable?", we have considered its entire life cycle, from its birth (caused from the death of a supermassive star) to its inevitable death (and collapse into a black hole) and have discussed the primary forces that operate inside a Neutron Star across these stages. We have also discussed where these forces come from, along with their inner mechanisms that allow these forces to be experienced. Finally, we pushed these forces to the extreme to discover substances such as Nuclear Pasta and Gluon-Quark Plasma.

Primarily, we have discovered that the upholding forces operating inside a Neutron Star are a combination of three – the Strong Nuclear Force, Neutron Degeneracy Pressure (which is a consequence of the Pauli Exclusion Principle), and the Quark Pressure inside neutrons, and therefore we can conclude that a Neutron Star is kept stable primarily due to these three forces combatting gravity; caused by the star's weight. Furthermore, we touched on these forces' strengths & limits, and considered what would occur if these forces were to be overpowered.

My Overall Findings

My original hypothesis for this question involved the Strong Nuclear Force providing the main force combatting gravity in a Neutron Star, along with the 'super-atom' at the star's core.

Even during my initial research, however, my suppositions were constantly changing – at one point in time I was convinced that ferromagnetism was a critical mechanism involved in a Neutron Star's main forces, and it was only after discovering Neutron Degeneracy Pressure and Quark Pressure did I begin to have a good grasp of what keeps a Neutron Star stable.

Through the completion of this report, however, I can definitively say that I now have a much deeper understanding of the inner mechanics operating in a Neutron Star. To develop my knowledge further, I will undergo more research into the properties of black holes (the entities that Neutron Stars develop into once they die) and investigate the properties of their singularity.

In conclusion, I strongly believe that I have answered the proposed question to a respectable level, and I am resultantly happy with the information I have learnt in the making of this report.

Total Word Count: 5,844

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https://www.youtube.com/watch?v=G5EjC7x8Egs.
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Kevin Boudreaux - https://www.angelo.edu/faculty/kboudrea/general/quantum_numbers/Quantum_Numbers.htm

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Janet Anderson & Megal Watzke (Published 23/2/2011) - https://www.nasa.gov/mission_pages/chandra/news/casa2011.html.

Elizabeth Howell (Published 30/8/2019) - https://www.space.com/colliding-neutron-stars-caued-massive-kilonova-explosion.html.

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Anton Petrov (Published 29/3/2018) - https://www.youtube.com/watch?v=VtcIIfXhu3Q.

(Note: Information regarding how I have used these sources in my report, along with the evaluation of the quality of each source, are displayed in my research log – please see my appendix for more information.)

Appendix

Appendix One: An afterword regarding my report's word count

I understand that my project's report (which has a word count of 5,844) is above this project's allocated word count of 5,000. However, I believe that, due to the complexity and scope of the topic I have covered in my report, I am unable to significantly reduce my word count without losing valuable detail and information.

Appendix Two: Presentation Board

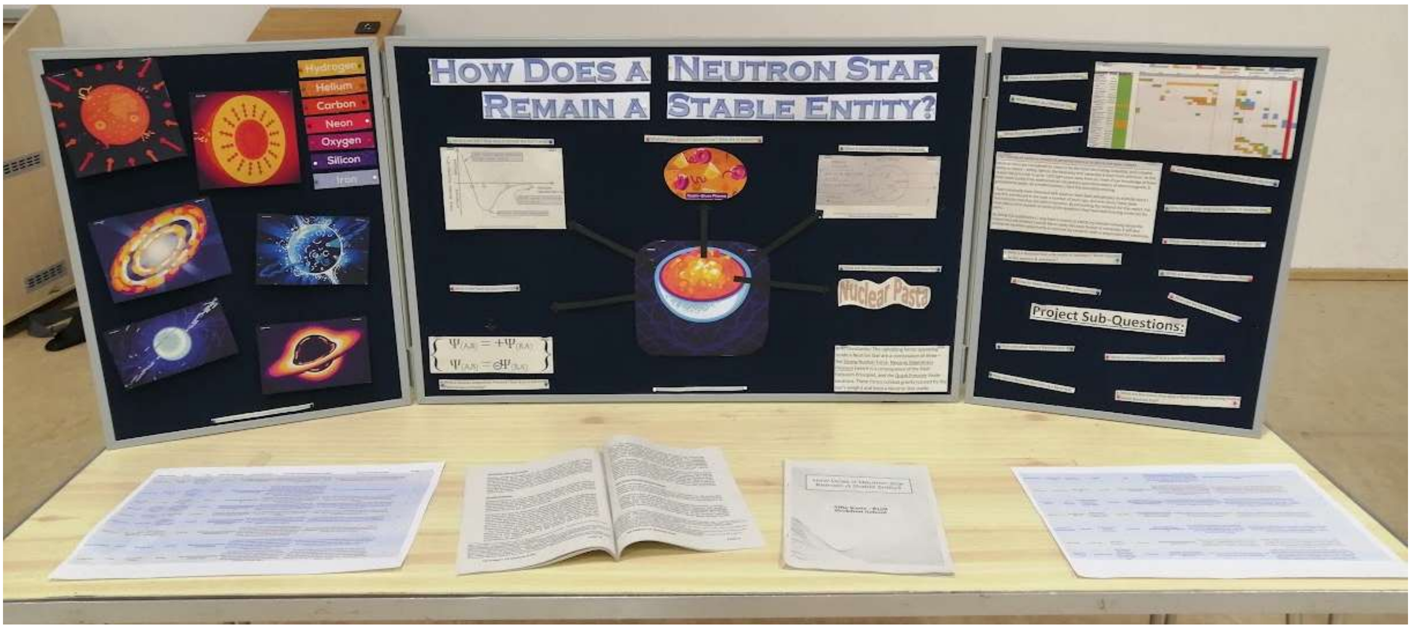


Figure 3 - My EPQ Presentation Board.
Left Side: Brief history of a Neutron Star. Centre Side: My main question & answers. Right Side: Project production, plan & sub-questions. Below this board are copies of my project report, along with extracts of my research log.

My presentation consisted of a 'science fair' board, which was displayed in the school hall for all to see and ask questions about. Some questions asked by my peers in this presentation included:

- "What was your main motive for doing your EPQ?"
- "Why Neutron Stars?"
- "How did you plan your time / research during this project?"
- "How did you reach the answer to this question?"
- "Did you enjoy the EPQ process? What tips would you give other students starting their own EPQ projects?"
- "Which sub-question in this project would you like to build upon more?"

Appendix Three: Presentation Resources (Sample)

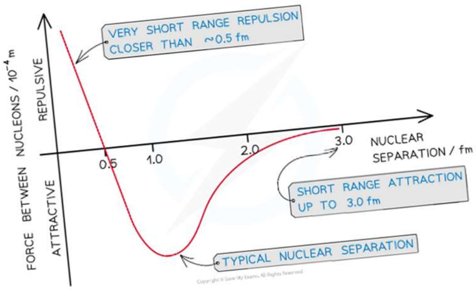
Project Sub-Questions:

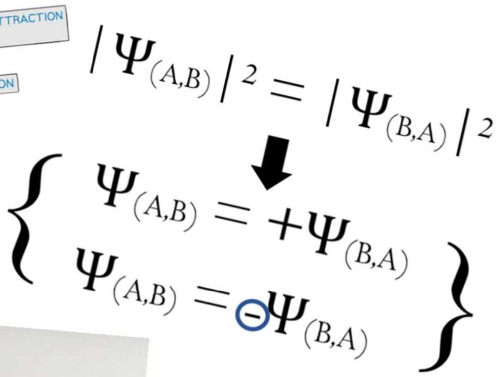
- How does a supermassive star collapse?
- Why is a Neutron Star *only* made of neutrons? What happens to the protons & electrons?
- How does a Neutron Star form vs a black hole?
- Why does a star stop fusing when it reaches Iron?

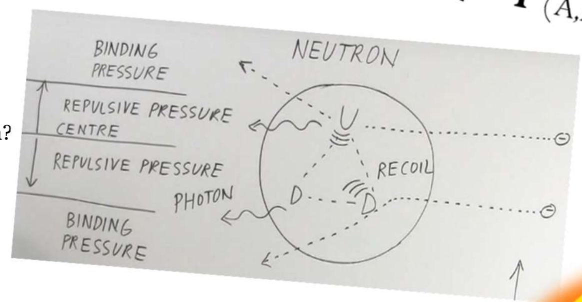
- What are the forces that stop a black hole from forming from a stable Neutron Star?
- What is the SNF? How does it combat the Star's weight?
- What makes up the wave function of an electron?
- What is the Pauli Exclusion Principle?
- What is Neutron Degeneracy Pressure? How does it link to the Pauli Exclusion Principle?
- What is Ferromagnetism? Is it a successful upholding force?

- What makes up the neutrons in a Neutron Star?
- What is Quark Pressure? How does it operate?
- What makes up a Neutron Star?
- What are the properties and structure of Nuclear Pasta?
- What is at the core of a Neutron Star? What are its properties?

- How and when does a Neutron Star die?
- What happens when a Neutron Star dies?
- What are pulsars? Are they Neutron Stars?
- How do heavy elements in the universe form?
- How can we detect Neutron Stars?







Brief Conclusion: The upholding forces operating inside a Neutron Star are a combination of three – the Strong Nuclear Force, Neutron Degeneracy Pressure (which is a consequence of the Pauli Exclusion Principle), and the Quark Pressure inside neutrons. These forces combat gravity (caused by the star's weight) and keep a Neutron Star stable.