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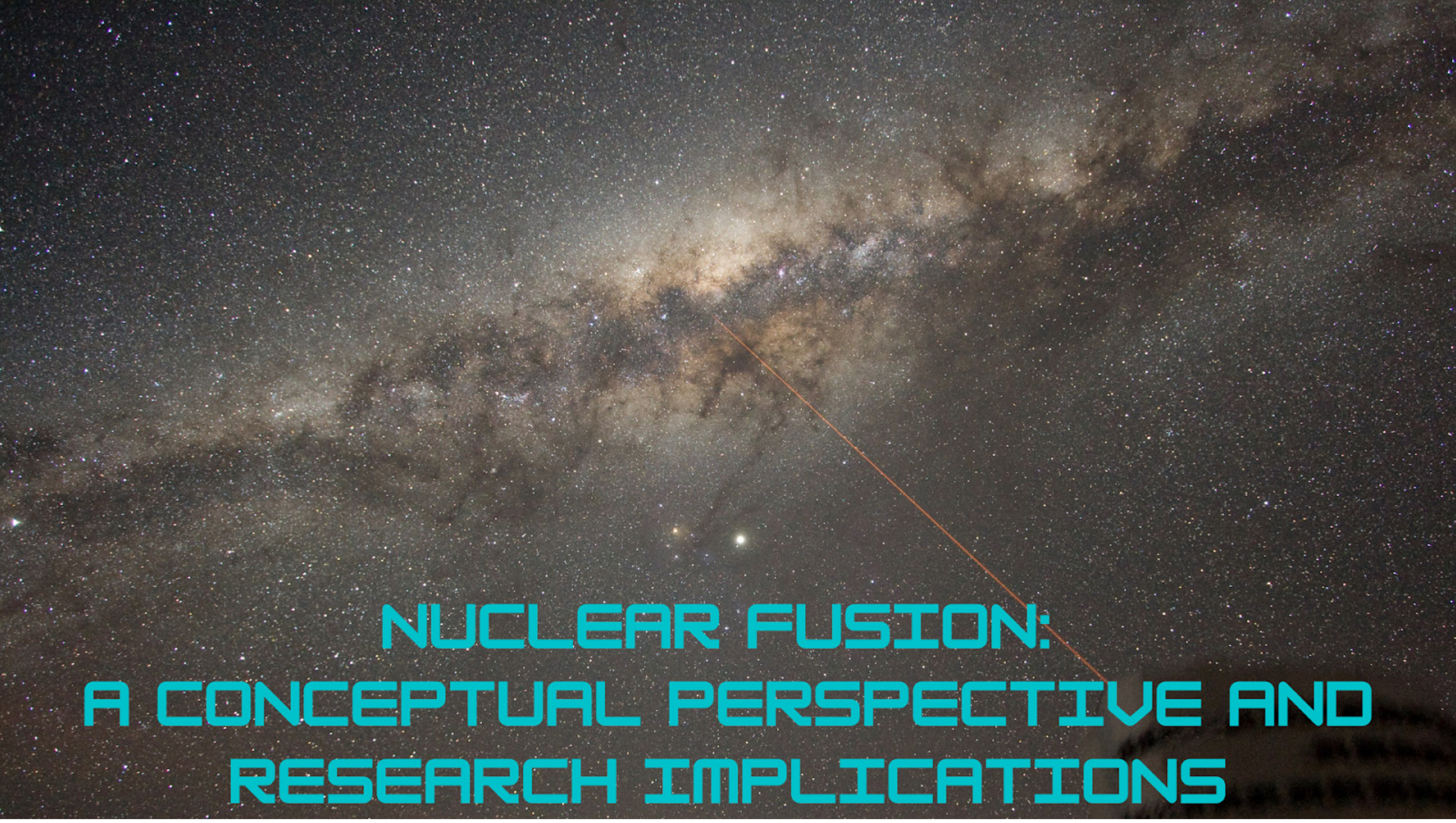

NUCLEAR FUSION: A CONCEPTUAL PERSPECTIVE AND RESEARCH IMPLICATIONS

BY COREY DODSON

Image Credit: ESO/Yuri Beletsky

During the first few seconds of the universe's existence, lighter elements combined into heavier elements–such as hydrogen into helium and helium into lithium—in a process known as *nucleosynthesis*. Over the course of the universe's evolution, stars, in both life and death, have formed most of the elements on the periodic table. For roughly 4.5 billion years, the sun has provided energy to the solar system, making life on Earth possible. Indeed, the universe, as humanity observes it, and life on Earth would not exist without *nuclear fusion*—the process by which two or more atomic nuclei combine to form heavier atomic nuclei, releasing a tremendous amount of energy. In fact, the fusion of hydrogen into helium that occurs in a star's core is precisely how astronomers define a *true star*, as well as the reason why stars shine.

Researchers have recreated this natural process in fusion reactors in order to harness the energy it releases, but the reactors are not yet efficient because the energy needed to begin the reaction far exceeds the energy released. In this dire age of environmental calamity, nuclear fusion reactors, in conjunction with other sources of renewable energy, can provide a solution for the energy crisis once they are efficient. Nuclear reactors are carbon-emission-free, and they use deuterium and tritium (two heavier isotopes of hydrogen) as fuel, which are inexpensive and easily attainable.[1] Theoretically, a mere few grams of this fuel can provide enough energy for one person for

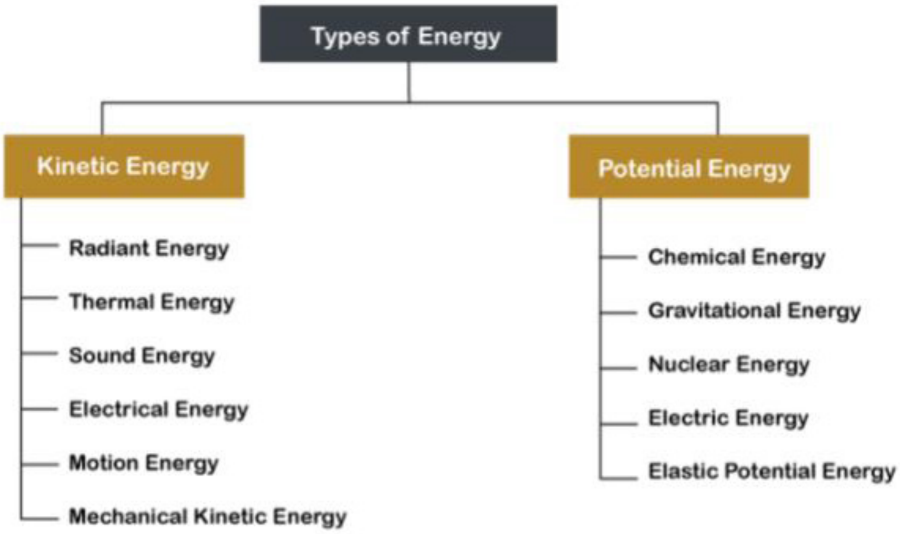

Figure 1a: Energy comes in many different forms. *Kinetic energy is the energy associated with motion and potential energy is energy stored within a system that has the 'potential' to be converted into kinetic energy. Kinetic energy can convert into other forms of energy as well.*

several decades.[1] The physics of fusion reactions within the core of stars is inherently beautiful, as it connects fundamental laws and forces, special relativity, and quantum mechanics, and recent research on fusion reactors has made progress toward attaining efficiency.

THE PRINCIPLE OF THE CONSERVATION OF ENERGY AND THE FUNDAMENTAL FORCES OF NATURE

All of physics is based on a few fundamental laws of nature, one of which is the conservation of energy. This principle states that energy in an isolated system can neither be created nor destroyed; it merely changes into different forms and is always conserved.

Furthermore, there are four fundamental forces of nature: gravity, the electromagnetic force, the weak force, and the strong force. The weak force is responsible for radioactive decay, whereas the strong force is responsible for holding atomic nuclei together and facilitating fusion. In addition, the distance over which the strong force can act is tiny: only 10^{-15} meters (femtometer).[2] Thus, atomic nuclei must be very close together for the force to occur and the fusion reaction to begin.

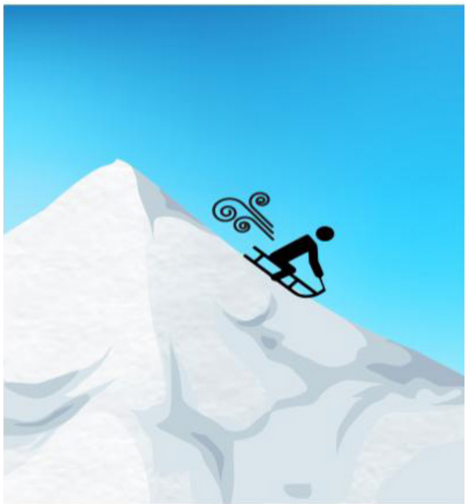

Figure 1b: Imagine a sled on a hill. *The potential energy of this system is determined by the hill's height, which, in turn, determines the total kinetic energy the sled will eventually possess. As the sled goes down the hill, its potential energy converts into kinetic energy, which increases as the sled gains velocity. In addition, the friction between the sled and ground converts some of the kinetic energy into heat, and it also converts into the sound one hears as the sled moves. The total energy is conserved in this situation; it just changed into different forms.*

The electromagnetic force pertains to both electric and magnetic forces. A basic principle of electric forces is that like charges experience a repulsive force between them, while opposite charges experience an attractive force.

ENERGY-MASS EQUIVALENCE

The energy released in a fusion reaction is not possible without energy-mass equivalence from special relativity. Many people may be aware of the famous equation derived by Albert Einstein, $E=mc^2$, which states that the total energy of a particle with mass at rest is proportional to its mass by a factor of the speed of light squared. A major implication of this equation is energy-mass equivalence, meaning that mass is a form of energy. Thus, mass can convert into energy and energy can convert into mass with both quantities conserved. Additionally, since the speed of light squared has a magnitude of roughly 9×10^{16}, a small amount of mass can be converted into a large amount of energy. In fact, a particle's mass is described in terms of its rest energy by particle physicists. For example, the electron has a mass of roughly 0.51 mega electron-volts (MeV, a unit of energy).[i]

QUANTUM MECHANICS

As for quantum mechanics, nuclear fusion is not possible without quantum tunneling for many stars, including the sun. In both cases for Figure 3a, the hill is a *potential barrier*. Classically, the final result of the cars' ascension can be predicted, beyond a shadow of a doubt, once the values for the potential energy of the system and total energy of the particle are known. At subatomic and atomic levels, however, the deterministic nature of classical mechanics crumbles, revealing quantum mechanics' probabilistic nature.

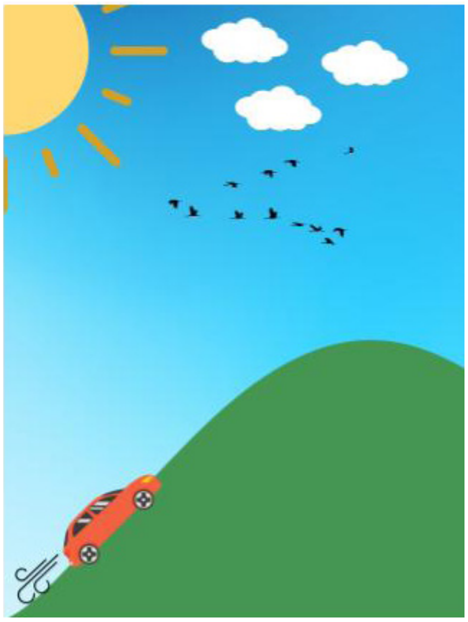

Figure 2a: Now imagine a car with kinetic energy heading towards a hill. *In a classical sense, as the car begins to ascend the hill, its kinetic energy converts back into potential energy, and the result of this ascension depends on how much kinetic energy the car possesses. If the kinetic energy is less than the potential energy, then the car fully converts the kinetic energy into potential energy, stops before reaching the top, then rolls back down the hill, forever bound to the system. If the kinetic energy is greater than the potential energy, then the car reaches the top and descends along the other side, forever free from the system.*

Thus, if the total energy of the particle is less than the maximum potential energy of the system, then there's a probability that the particle counterintuitively tunnels through the potential barrier and is observed on the other side.[3] In the classical example, there's a chance that the car will 'tunnel through' the hill. Although this phenomenon defies the logic of everyday experience, it has been experimentally observed countless times and has far reaching applications, such as in circuit resistors and nuclear fusion.

NUCLEAR FUSION IN THE SUN

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[i] *A particle's respective antiparticle has the same mass but an opposite charge; the electron has a charge of -1, so the electron's antiparticle—the positron—has the same mass and a charge of +1. An example of energy-mass equivalence is* particle annihilation*: when a particle and its respective antiparticle collide, they convert into light. eletsky*

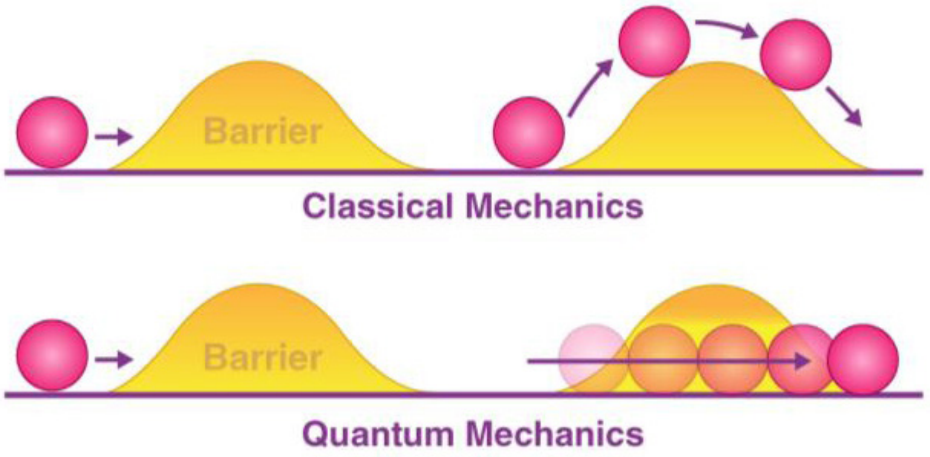

Figure 2b: Classical mechanics is deterministic, so with known information one can predict with absolute certainty some future observation. *Quantum mechanics, however, is probabilistic, so there's only a chance that one will observe a specific measurement—each possible measurement has an associated probability. Furthermore, consider a particle such as a proton, with some total energy (the sum of its kinetic energy and mass energy). As a consequence of the wave-like nature of particles, if the total energy of the particle is less than the maximum potential energy of the system, then there's a chance that one observes the particle past the potential barrier. Additionally, if the particle's total energy is greater than the potential energy of the system, then there's no guarantee that one observes the particle past the potential barrier.*[3]

As one might recall, the strong force is responsible for fusion reactions and its range is 10^{-15} meters, and particles with like charges experience a repulsive electric force. As a general example, suppose we have protons in the core of the sun, which is an environment with immense heat and pressure. Additionally, when particles with like charges get closer, the potential energy of the system increases; as the distance approaches zero, the potential energy becomes infinitely large and the particles experience extreme electric repulsion, becoming a potential barrier known as a *coulomb barrier*.[2] The heat and pressure inside the core of the sun allows the protons to come close together, but the energy that the particles gain, in a classical sense, is essentially insufficient to overcome the coulomb barrier.[2]

However, as a consequence of quantum tunneling, there is an increased probability that the protons tunnel through this coulomb barrier, entering the range of the strong force to begin the fusion reaction.[2] As an example of the astounding accuracy of quantum theory, the probability that the proton tunnels is related to the rate of fusion reactions in the core of the sun.[4]

Moreover, the total initial mass is less than the mass after the reaction—the lost mass gets converted into an astronomical amount of energy in the form of heat. The goal of fusion reactors is to convert this heat into electric energy. As a specific example, during the proton-proton chain, a fusion reaction that occurs within the core of stars, four hydrogen atoms fuse into a helium atom, with an astronomical amount of energy released, despite the small difference between the final mass of helium nucleus and the initial mass of the four hydrogen nuclei.[5]

RECENT RESEARCH

As previously mentioned, fusion reactors are not yet efficient, but researchers have recently made progress. In 2021, researchers at the U.S. National Ignition Facility achieved *plasma burning* with their fusion reaction, which is when the heat generated by fusion becomes sufficient to sustain a chain reaction.[6] Indeed, plasma burning is the reason why fusion reactions continue to occur within the core of stars for billions of years. On February 9, 2022, researchers from the Joint European Torus (JET) project—a tokamak fusion reactor in Oxfordshire, UK—revealed that they generated 59 megajoules (a unit of energy) in a recent fusion reaction, which not only broke but doubled their own previous 24-year-old record.[7] Although these are significant achievements, feasible fusion reactors are estimated to be a couple decades away from being attained.[8]

The attainment of efficient nuclear reactors will be a paradigm shift in energy production, as they possess the potential to power the entire planet for thousands of millennia—inexpensively and at no risk

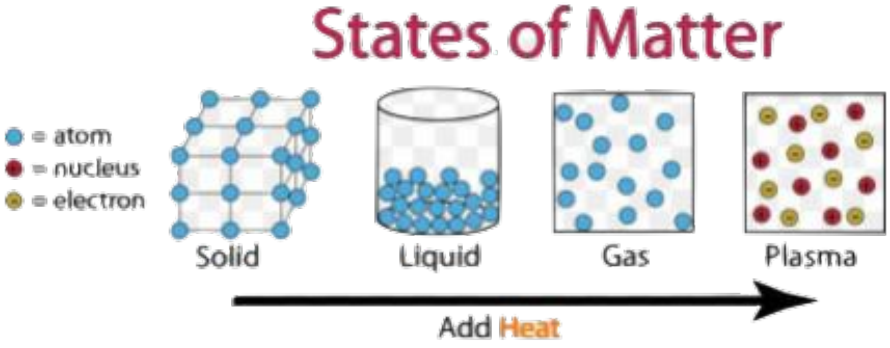

Figure 3: Plasmas are essential for fusion reactions. *Plasmas are gases in which the particles have charges. In an environment with extremely high temperature (such as the core of a star), electrons gain a lot of energy and are able to overcome the electrical force binding them to an atomic nucleus, leaving only the atomic nucleus with a positive charge and free negatively-charged electrons. As such, the hydrogen atoms in the core of a star are just protons, which also gain kinetic energy from the heat.*

to the environment.[1] However, this does not negate the necessity of using currently feasible sources of renewable energy, which should have been transitioned to decades ago. To solve what is arguably the greatest problem in modern physics, efficient nuclear reactors will require creative minds from a diverse range of fields to apply their talents for the sake of all humanity.

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