Quantum Mechanics_Nuclear astrophysics

Nuclear astrophysics is an interdisciplinary branch of physics involving close collaboration among researchers in various subfields of nuclear physics andastrophysics, with significant emphasis in areas such as stellar modeling, measurement and theoretical estimation of nuclear reaction rates, cosmology,cosmochemistry, gamma ray, optical and X-ray astronomy, and extending our knowledge about nuclear lifetimes and masses. In general terms, **nuclear astrophysics** aims to understand the origin of the chemical elements and the energy generation in stars.

History

The basic principles of explaining the origin of the elements and the energy generation in stars were laid down in the theory of nucleosynthesis which came together in the late 1950s from the seminal works of Burbidge, Burbidge, Fowler, and Hoyle in a famous paper[1] and independently by Cameron.[2] Fowler is largely credited with initiating the collaboration between astronomers, astrophysicists, and experimental nuclear physicists which is what we now know as **nuclear astrophysics**.

The basic tenets of **nuclear astrophysics** are that only isotopes of hydrogen andhelium (and traces of lithium, beryllium, and boron) can be formed in a homogeneous big bang model (see big bang nucleosynthesis), and all other elements are formed in stars. The conversion of nuclear mass to kinetic energy (by merit of Einstein's famous mass-energy relation in relativity) is the source of energy which allows stars to shine for up to billions of years. Many notable physicists of the 19th century, such as Mayer, Waterson, von Helmholtz, and Lord Kelvin, postulated that the Sun radiates thermal energy based on convertinggravitational potential energy into heat. The lifetime of the Sun under such a model can be calculated relatively easily using the virial theorem, yielding around 19 million years, an age that was not consistent with the interpretation ofgeological records or the then recently proposed theory of biological evolution. Aback-of-the-envelope calculation indicates that if the Sun consisted entirely of afossil fuel like coal, a source of energy familiar to many people, considering the rate of thermal energy emission, then the Sun would have a lifetime of merely four or five thousand years, which is not even consistent with records of human civilization. The now discredited hypothesis that gravitational contraction is the Sun's primary source of energy was, however, reasonable before the advent ofmodern physics; radioactivity itself was not discovered by Becquerel until 1895[3]Besides the prerequisite knowledge of the atomic nucleus, a proper understanding of stellar energy is not possible without the theories of relativity and quantum mechanics.

After Aston demonstrated that the mass of helium is less than four times the mass of the proton, Eddington proposed that in the core of the Sun, through an unknown process, hydrogen was transmuted into helium, liberating energy.[4] 20 years later, Bethe and von Weizsäcker independently derived the CN cycle,[5][6]the first known nuclear reaction cycle which can accomplish this transmutation; however, it is now understood that the Sun's primary energy source is the pp-chains, which can occur at much lower energies and are much slower than catalytic hydrogen fusion. The time-lapse between Eddington's proposal and the derivation of the CN cycle can mainly be attributed to an incomplete understanding of nuclear structure, and a proper understanding of nucleosynthetic processes was not possible until Chadwick discovered theneutron in 1932[7] and a contemporary theory of beta decay developed. Nuclear physics gives a self-consistent picture of the energy source for the Sun and its subsequent lifetime, as the age of the solar system derived from meteoriticabundances of lead and uranium isotopes is about 4.5 billion years. A star the mass of the Sun has enough nuclear fuel to allow for core hydrogen burning on the main sequence of the HR-diagram via the pp-chains for about 9 billion years, a lifetime primarily set by the extremely slow production of deuterium,

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}D + e^{+} + \nu_{e} + 0.42\ \text{MeV}$$

which is governed by the nuclear weak force.

Predictions

The theory of stellar nucleosynthesis reproduces the chemical abundances observed in the solar system and galaxy, which from hydrogen to uranium, show an extremely varied distribution spanning twelve orders of magnitude (one trillion).[8] While impressive, these data were used to formulate the theory, and ascientific theory must be predictive in order to have any merit. The theory of stellar nucleosynthesis has been well-tested by observation and experiment since the theory was first formulated.

The theory predicted the observation of technetium (the lightest chemical element with no stable isotopes) in stars,[9] observation of galactic gamma-emitters such as ^{26}Al[10] and ^{44}Ti,[11] observation of solar neutrinos,[12] and observation of neutrinos from supernova 1987a. These observations have far-reaching implications. ^{26}Al has a lifetime a bit less than one million years, which is very short on a galactic timescale, proving that nucleosynthesis is an on-going process even in our own time. Work which lead to the discovery of neutrino oscillation, implying a non-zero mass for the neutrino and thus not predicted by the Standard Model of particle physics, was motivated by a solar neutrino flux about three times lower than expected, which was a long-standing concern in the nuclear astrophysics community such that it was colloquially known simply asthe Solar neutrino problem. The observable neutrino flux from nuclear reactors is much larger than that of the Sun, and thus Davis and others were primarily motivated to look for solar neutrinos for astronomical reasons.

Future work

Although the foundations of the science are bona fide, there are still many remaining open questions. A few of the long-standing issues are helium fusion(specifically the ^{12}C(α,γ)^{16}O reaction[13]), the astrophysical site of the r-process, anomalous lithium abundances in Population III stars, and the explosion mechanism in core-collapse supernovae.

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