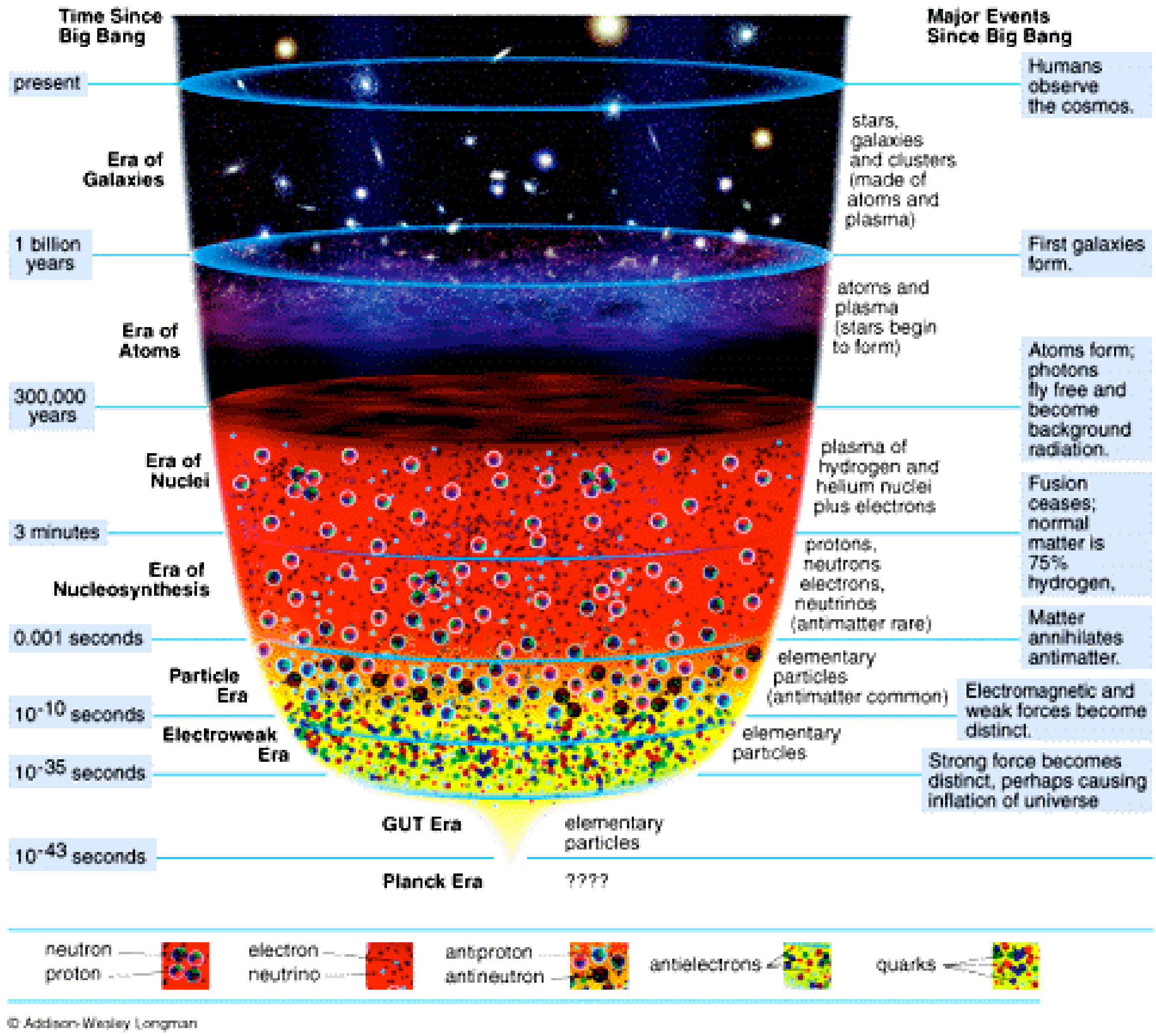
Overview

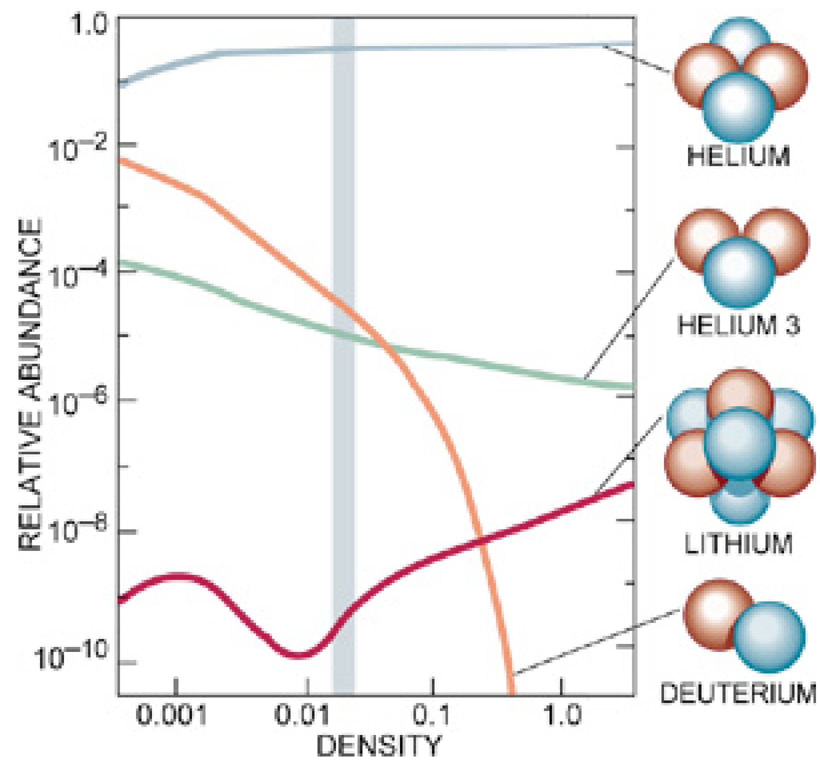
Big Bang nucleosynthesis and cosmic microwave background



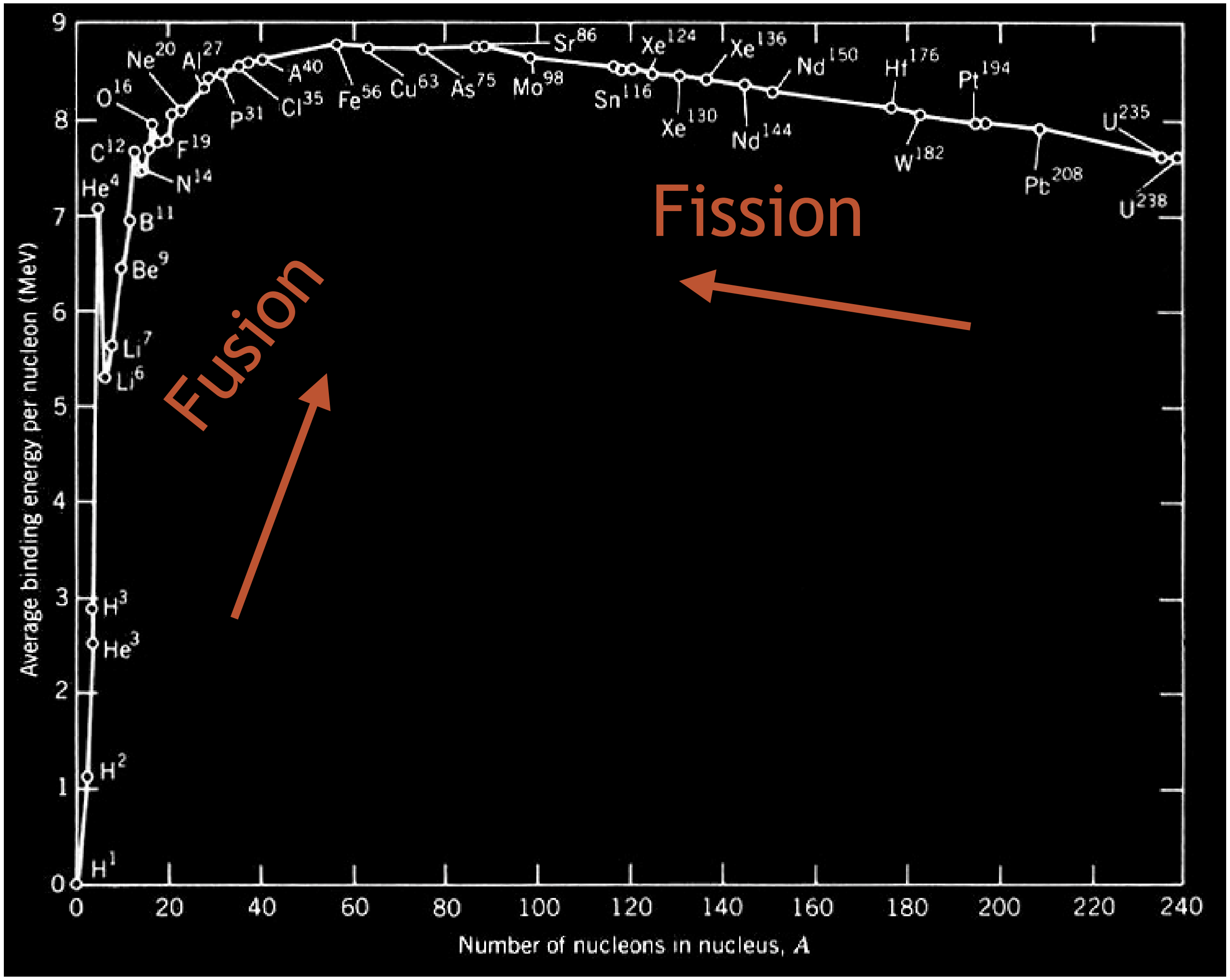
Overview

Big Bang nucleosynthesis and cosmic microwave background

Elements observed in the universe were created in 2 ways. Light elements (deuterium, helium and lithium) were created at 100s from after the Big-Bang when neutrons and protons combine. The universe cools so rapidly that no other elements are formed. ALL the other heavier elements must have been synthesized in stars!



Binding energy per nucleus as a function of the atomic mass, A



Thermonuclear Reactions: Energy Release & definitions

particle, a strikes nucleus X, producing nucleus Y and particle b:

$$a + X \longrightarrow Y + b$$

which is often written as X(a,b)Y

an exothermic nuclear reaction is one in which energy is released e.g.

$$a + X \longrightarrow Y + b + Q$$

where $Q > 0$, is the difference between the energy of the system (X+a) and (Y+b).

the reaction cross section for an incident particle a, colliding with a target X is defined by:

$$\sigma_{X,a}(v) = \frac{\text{no of reactions per no of particles X unit time}}{\text{no of particles a per unit area per unit time}}$$

where v is the relative velocity of the particles

The reaction rate per particle pair = $\langle \mathrm{v}\sigma_{Xa}(\mathrm{v}) \rangle$
where the <> denotes the average over a Maxwellian distribution of relative velocities v

the reaction rate = $N_X N_a \langle \mathrm{v}\sigma_{Xa}(\mathrm{v}) \rangle$

the lifetime of nucleus X wrt the reaction with a is defined by:

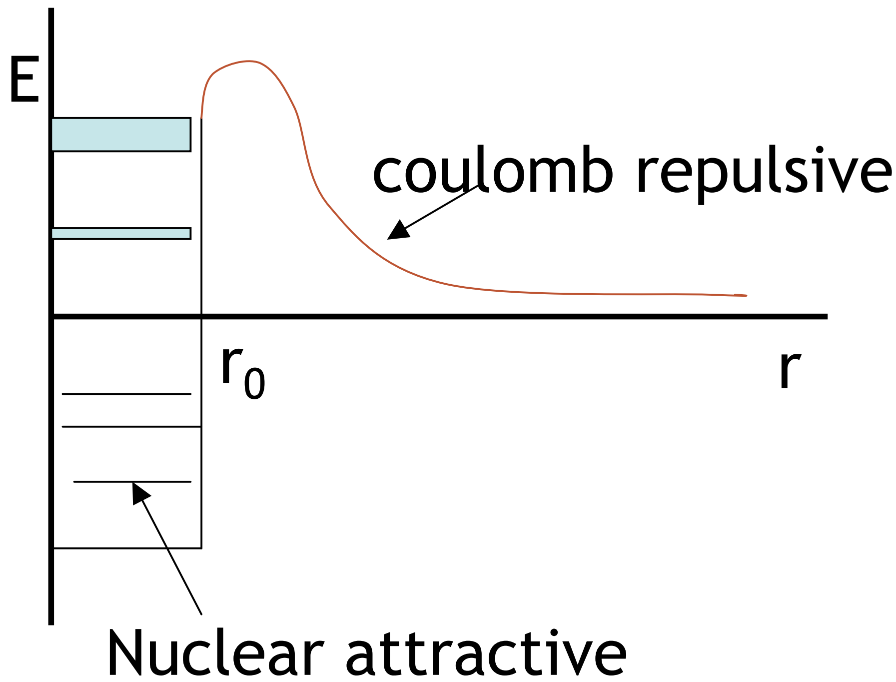
$$\tau_{X,a} = \frac{1}{N_a \langle \mathrm{v}\sigma_{Xa}(\mathrm{v}) \rangle}$$

the total lifetime, of nucleus X is given

$$\frac{1}{\tau_X} = \sum_{a_i} \frac{1}{\tau_{X_i a_i}}$$

problem 1: Coulomb barrier - protons have to overcome electrostatic repulsion

the cross section for nuclear reaction: 2 nuclei of positive charges Z_1 and Z_2 have potential as shown



the coulomb energy

$$V \sim 1/(4\pi\varepsilon)\ Z_1 Z_2 e^2/r$$

at touching distance

$$\sim 1\ \text{MeV}\ Z_1 Z_2 / (A_1^{1/3} + A_2^{1/3})$$

classical solution:

in order to fuse they have to overcome the Coulomb barrier. However the typical thermal energy in the stellar interiors (KT ~ keV) is a factor of 1000 smaller than the Coulomb barrier. So CLASSICALLY two typical nuclei will stop at a distance about V/kT ~ 1000 larger than their touching distance, and bounce back.Therefore essentially no thermonuclear reactions can occur.(note the KT gives only the mean energy per nucleus but the nuclei are distributed on a Maxwellian. The number of nuclei in high E tail decreases as exp(-E/kT). So the number of nuclei decreases by a factor exp(-1000) = 10^{-434}

In stars the chances of finding a nucleus with kinetic energy large enough to overcome the Coulomb barrier is therefore essentially zero!!!

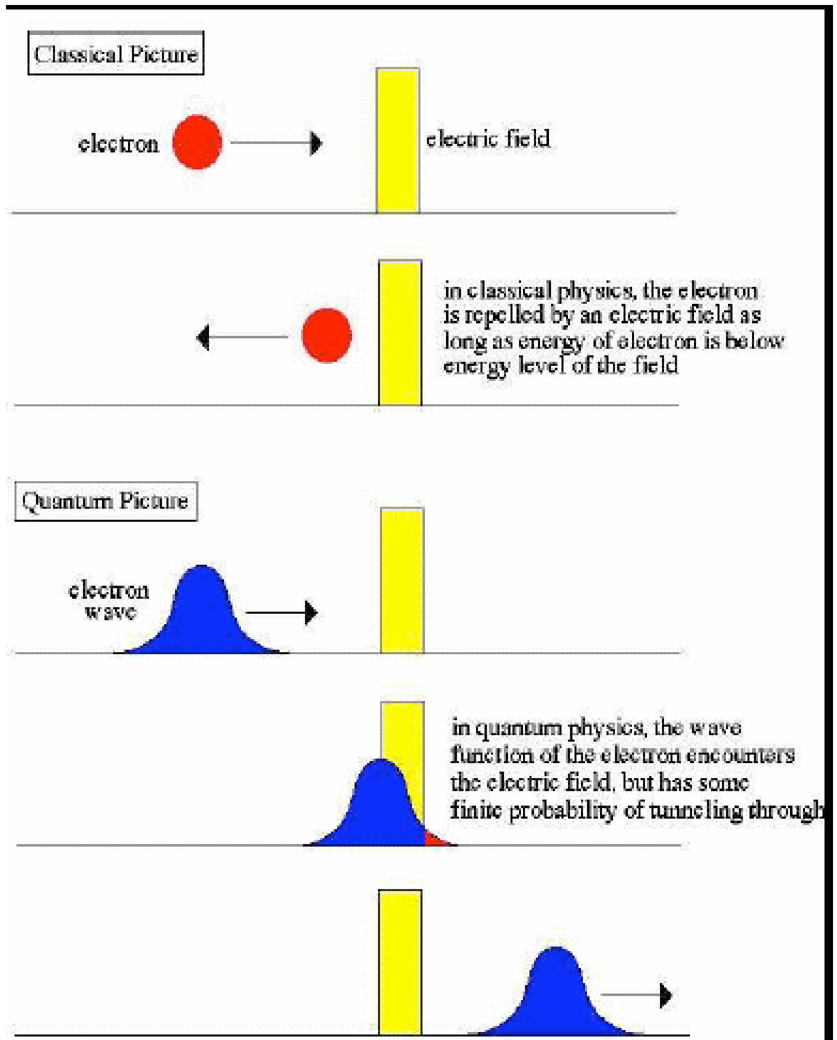
Sir Eddington (1882-1944)

Arthur Eddington thought that nuclear processes must be involved to account for the radiant energy of the sun, but was criticized because the temperature was seen to be not hot enough when considered by classical physics alone.

His tongue-in-cheek reply to his critics: "*I am aware that many critics consider the stars are not hot enough. The critics lay themselves open to an obvious retort; we tell them to go and find a hotter place.*"

quantum mechanical solution:

However in Quantum Mechanics this difficulty is overcome by QUANTUM TUNNELING as it was first realized by Gamow: there is a finite probability for a particle to penetrate the Coulomb barrier even when it has an KE < E_c.



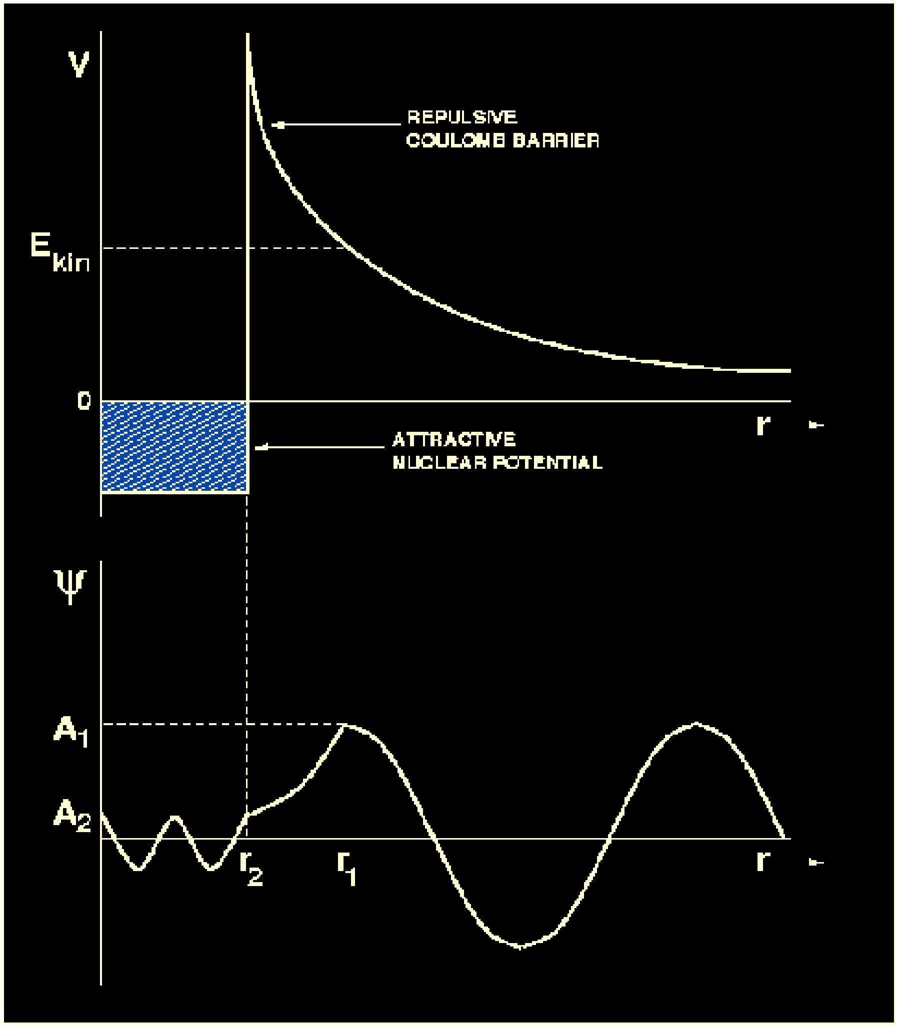


Fig. 2: Upper panel: A schematic plot of the potential energy V (i.e. the energy which one nucleus must have in order to approach another nucleus) versus separation between two nuclei. At large separations, the electrostatic repulsion dominates. For separations of $r<10^{-15}$m, the strong nuclear force takes over, allowing the two nuclei to fuse. Lower panel: A schematic plot of the wave function representing the penetration of a potential barrier by a nucleus whose kinetic energy of approach E_{kin} is below that of the barrier. The wave function oscillates sinusoidally in the inner and outer classically allowed regions and decays exponentially in the intervening classically forbidden region.

we will show that the cross section depends on 2 factors:

$S(E)/E \times P_{tunnel}(E)$

nuclear factor

probability of quantum tunnelling