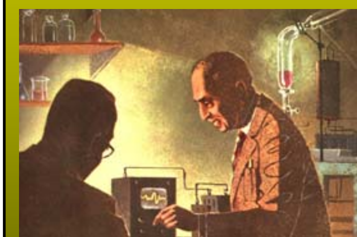
NUCLEAR FISSION- a Tunneling Process

Nuclear fission, described on p. 12.10, is an extremely rare process. A U nucleus will on average take 4.5 billion yrs. to undergo fission- although the frequency of oscillations inside the nucleus is ~ 10^{21} per second. This means a tunneling probability ~ 10^{-38} – a very small number. Actually all nuclei except Fe decay, but only a few do it fast enough to be seen, except for very heavy ones- which decay rather fast.

Kaiser Wilhelm Institute (Berlin) in 1938



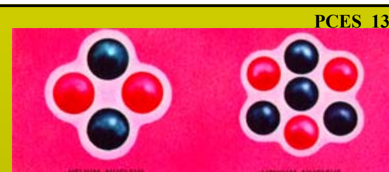
Hahn & Strassmann – the discovery of nuclear fission in Berlin (1938)

If a nucleus absorbs neutrons it can become much more unstable, undergoing fission with emission of several neutrons- giving the possibility of chain reaction. All this was worked out by Frisch & Meitner within days of hearing of the discovery of fission.

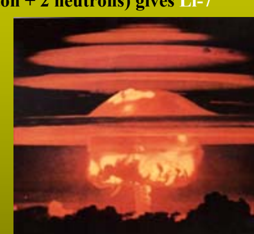
Neutron-induced fission- with accompanying emission of 2 neutrons

NUCLEAR FUSION

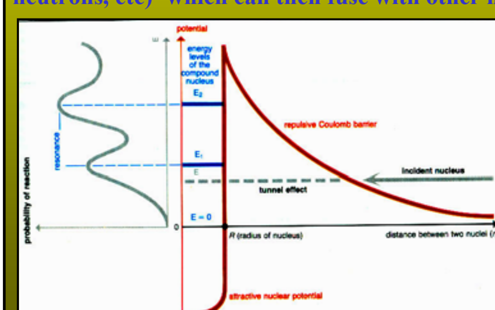
If high-energy charged particles approach a charged nucleus they will usually "bounce off" the strong repulsive potential (recall Rutherford scattering, page 11.5). However there is also a small probability they can tunnel through the barrier and fuse with the nucleus, forming a new heavier nucleus. This will get rid of its excess energy by re-emitting photons or a few sub-nuclear particles (protons, neutrons, etc)- which can then fuse with other nuclei.



A He-4 nucleus (2 protons, 2 neutrons) +H-3 (tritium-1 proton + 2 neutrons) gives Li-7



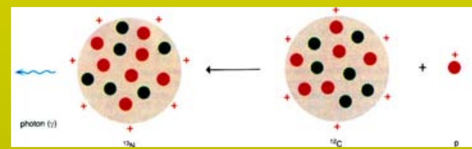
A H fusion bomb- as in the Sun, H fuses mainly to He.



A high energy particle coming from the right can tunnel through the Coulomb barrier to an energy level in the nucleus- a bound state of both together

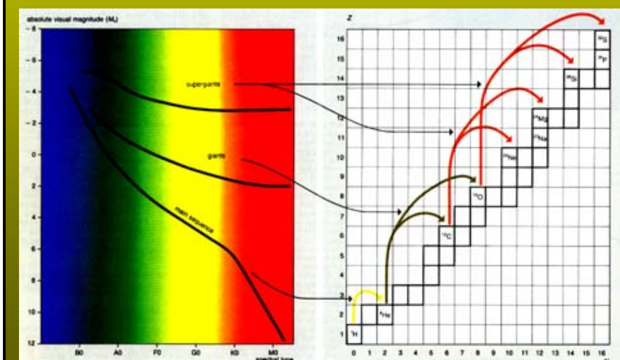
In most cases we will get scattering- the tunneling probability is very small. To increase it we need higher energy particles. Thus fusion takes place if the nuclei are rushing around at very high temperatures (roughly 10^8 K in a nuclear fusion bomb). The photons & other particles emitted come out with similar energies.

FUSION in STARS



A simple fusion process- a proton fuses with C-12 to make N-13, with emission of a photon.

This is extremely complex- there is a huge variety of interconnected chain reactions. For it to proceed the different nuclei must be at high T. The radiation emitted during the fusion keeps T high. Slowly the heavier elements up to Fe (whose nucleus has 26 protons and 30 neutrons) are synthesized- depending on the mass, this may take from 2 million to 100 billion yrs.To make heavier elements requires higher T; the star core heats up and it expands to a giant or a supergiant.



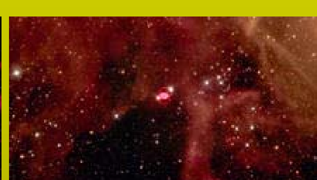
Some of the many nucleosynthesis preocesses involved in stars

However Fe is the most stable nucleus- after this one cannot go farther with fusion. The star has then run out of fuel. If it is a light star it will then collapse to a white dwarf, of planetary diameter, and cool over billions of years to a black dwarf.

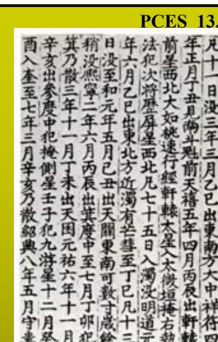
Massive stars behave differently…

NUCLEOSYNTHESIS in SUPERNOVAE

SN 1987A in the Larger Magellanic Cloud (lower left)



SN 1987A, v. high magnification, 10 yrs later


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

Observation of Crab Supernova in 1058 AD

A massive star ends its life in a spectacular collapse (taking only 10-50 secs), followed by explosive rebound, which converts a mass of several suns into energy ($E = mc^2$). This process creates almost all heavy elements in the universe.

The remaining stellar core has no radiation pressure from nuclear fusion to support it, & collapses to a neutron star or black hole. This still glows feebly, with occasional flares from accreting matter.

Centre of M1, in X-rays & in red light

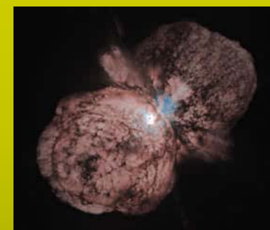
Crab Nebula M1 now, 945 yrs later- it is several light yrs across

The STUFF of LIFE

The material blown off from a supernovae is moving fast- sometimes >10,000 km/sec; it is rapidly dispersed around the galaxy. Material blown off from unstable giant or supergiant stars contributes even more to the interstellar medium.

Supernova material crashing into the medium creates shock waves which compress the medium & initiate gravitational collapse of gas & dust clouds. The supernova material seeds these clouds with heavy elements- from which the planets, and we ourselves, are made.

IC 418- the ‘spirograph’ planetary nebula



Blow-off from Eta Carinae in 1880-90 obscures the central star

The Vela supernova remnant extends over many light years, still glowing.

A close-up shows a shock front (& a meteor track on the photo)