Nucleosynthesis – the origin of the elements

Atomic mass units (amu):

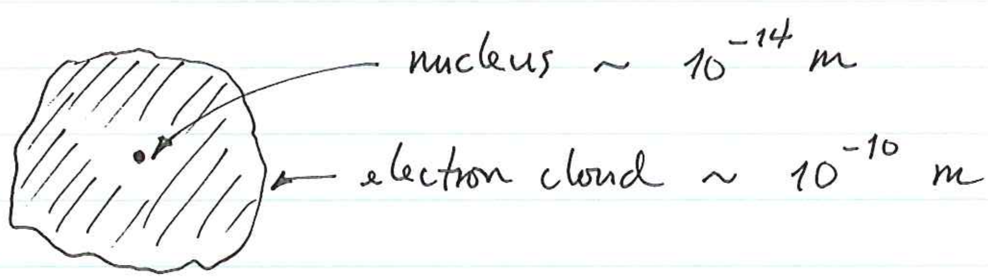
$$1 \text{ amu} = \frac{1}{12} \times \text{mass of } {}^{12}C = 1.67 \cdot 10^{-27} \text{ kg}$$

most common isotope of carbon

Proton — 1.00758 amu
Neutron — 1.00897 amu
Electron — $5.5 \cdot 10^{-4}$ amu

Z – atomic number (number of protons)
N – number of neutrons
$A = Z + N$ – number of nucleons

Typical dimensions



Electrons weigh only 0.02 – 0.03 % of atom, but take up almost all the space

"Matter is mostly empty space"

Density of ^{16}O nucleus

$$\rho_{nucleus} \approx \frac{16\,(1.67 \cdot 10^{-27}\ kg)}{\frac{4}{3}\pi\,(10^{-14}\ m)^3} \approx 6 \cdot 10^{15}\ kg/m^3$$

$$\boxed{\rho_{nucleus} \approx 10^{12}\ \bar{\rho}_{\oplus}}$$

Table of nuclides:

Plot all stable isotopes Z versus N

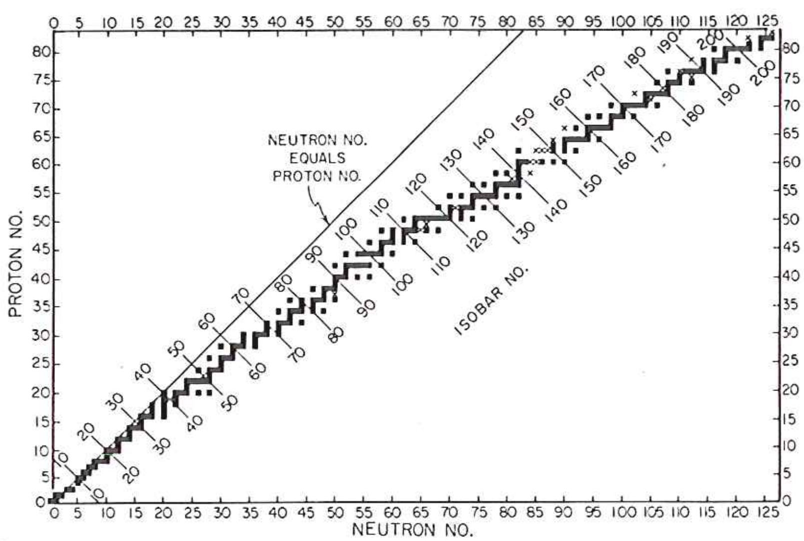
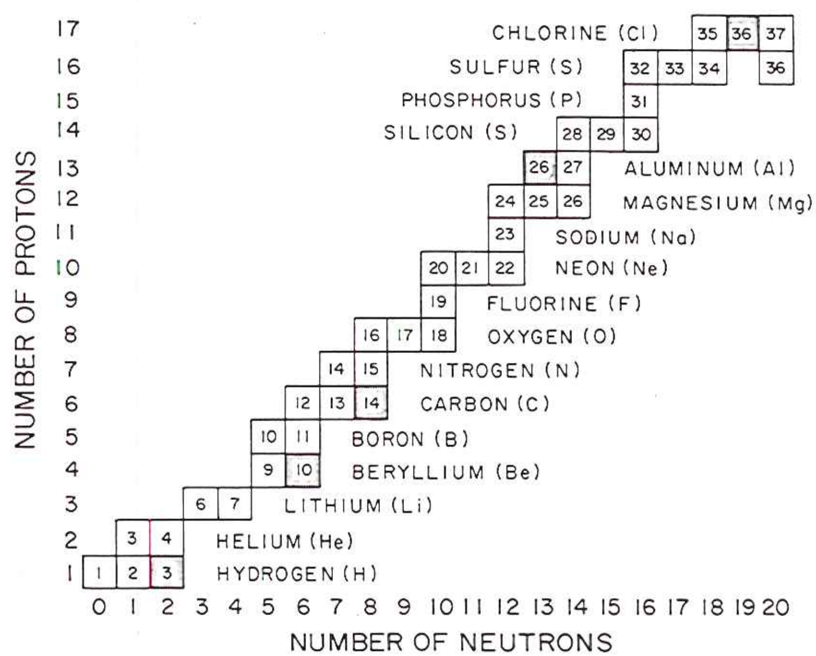
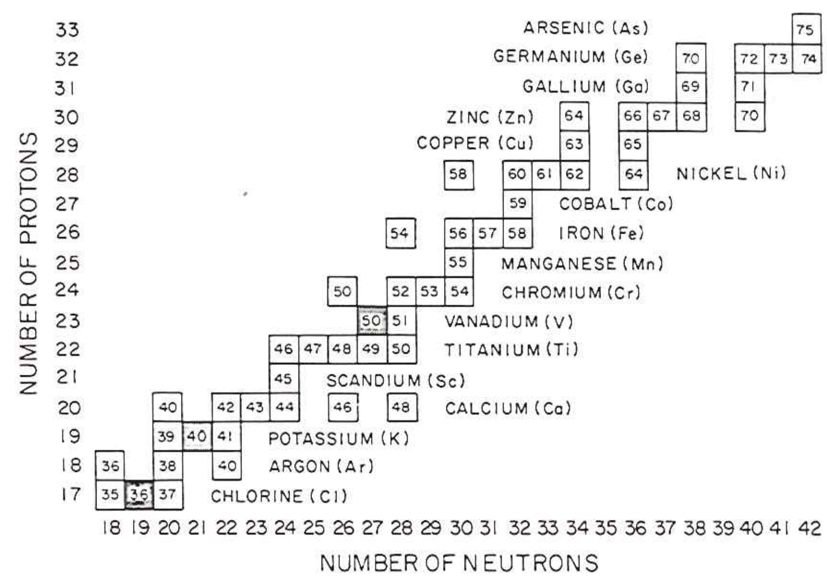


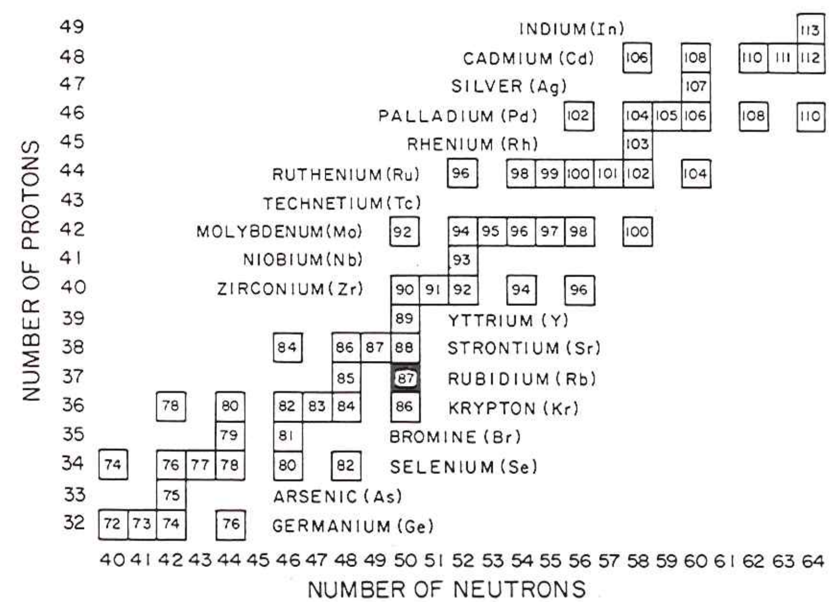
Figure 2-2. Stable nuclide configurations: The squares represent stable combinations of neutrons and protons. The x's represent radioactive nuclides whose half-lives are so long that they survive billions of years after their formation in stars. All the remaining combinations are radioactive with half-lives sufficiently short that they are no longer present in the solar system. Nuclides lying along the same horizontal line (i.e., those with the same proton number) are referred to as isotopes. Those falling along the same vertical line (i.e., those with the same number of neutrons) are referred to as isotones. Those falling along the same diagonal line (i.e., those with the same number of nuclear particles) are called isobars. The diagram terminates with the heaviest stable nuclide (^{209}Bi).

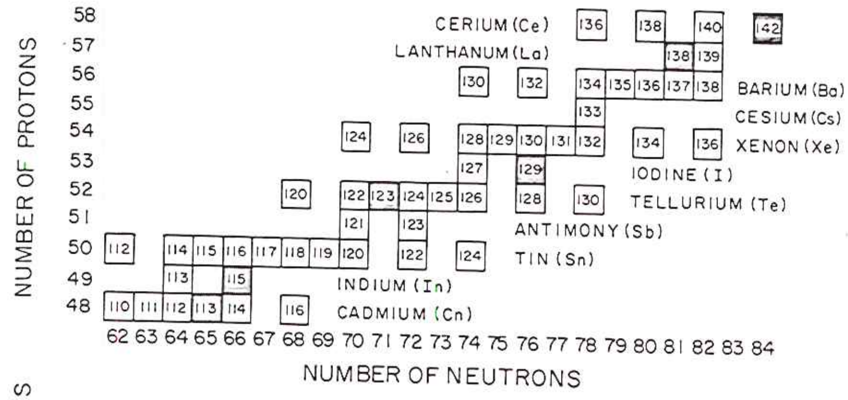
Heaviest stable element ^{209}Bi $(Z = 83)$

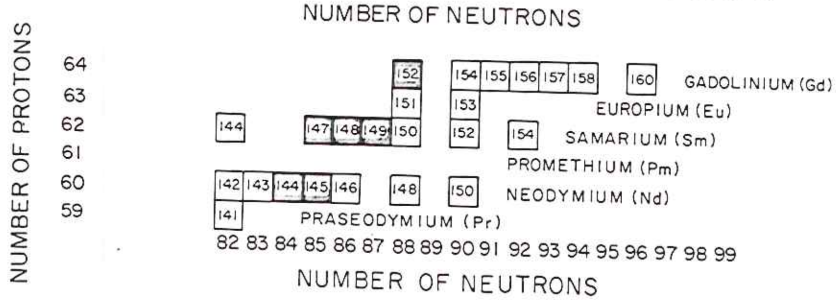
Figure 2-13. Chart of the nuclides: Shown in this series of diagrams are all the nuclides present in nature. The black squares represent radioactive isotopes. Some of these are long-lived remnants of element production in stars. Others are being produced in very small quantities by cosmic rays bombarding our atmosphere. To avoid confusion, the decay chains of long-lived thorium and uranium isotopes are shown separately.

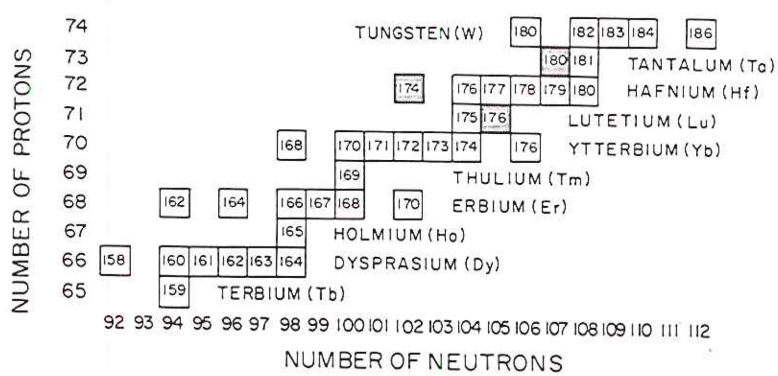


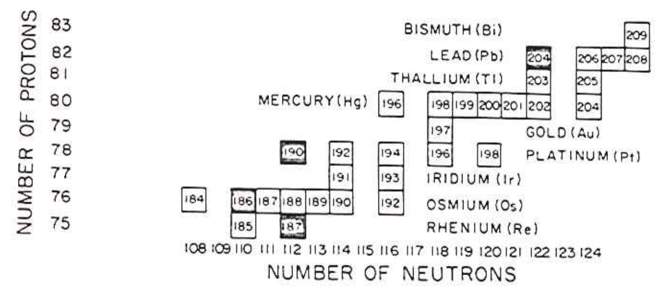


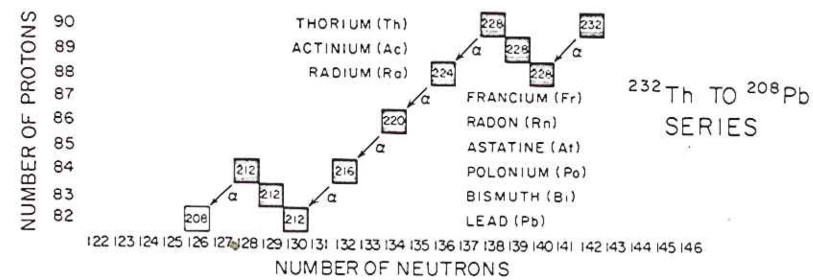


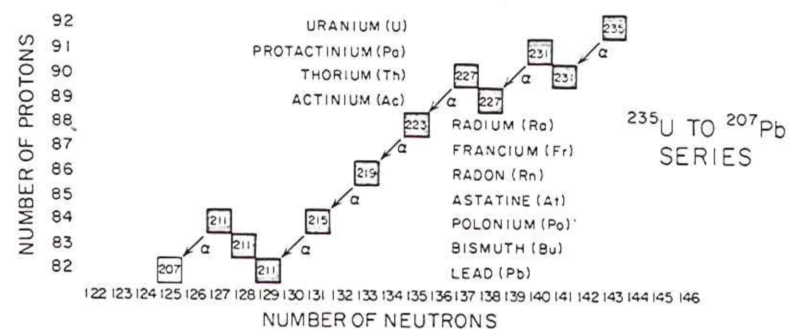

CERIUM (Ce)
LANTHANUM (La)
BARIUM (Ba)
CESIUM (Cs)
XENON (Xe)
IODINE (I)
TELLURIUM (Te)
ANTIMONY (Sb)
TIN (Sn)
INDIUM (In)
CADMIUM (Cn)
NUMBER OF PROTONS
NUMBER OF NEUTRONS

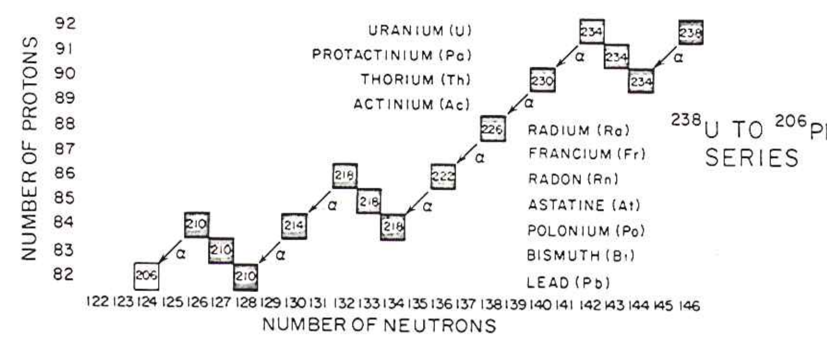

GADOLINIUM (Gd)
EUROPIUM (Eu)
SAMARIUM (Sm)
PROMETHIUM (Pm)
NEODYMIUM (Nd)
PRASEODYMIUM (Pr)
NUMBER OF PROTONS
NUMBER OF NEUTRONS


TUNGSTEN (W)
TANTALUM (Ta)
HAFNIUM (Hf)
LUTETIUM (Lu)
YTTERBIUM (Yb)
THULIUM (Tm)
ERBIUM (Er)
HOLMIUM (Ho)
DYSPRASIUM (Dy)
TERBIUM (Tb)
NUMBER OF PROTONS
NUMBER OF NEUTRONS


BISMUTH (Bi)
LEAD (Pb)
THALLIUM (Tl)
MERCURY (Hg)
GOLD (Au)
PLATINUM (Pt)
IRIDIUM (Ir)
OSMIUM (Os)
RHENIUM (Re)
NUMBER OF PROTONS
NUMBER OF NEUTRONS


THORIUM (Th)
ACTINIUM (Ac)
RADIUM (Ra)
FRANCIUM (Fr)
RADON (Rn)
ASTATINE (At)
POLONIUM (Po)
BISMUTH (Bi)
LEAD (Pb)
232Th TO 208Pb SERIES
NUMBER OF PROTONS
NUMBER OF NEUTRONS


URANIUM (U)
PROTACTINIUM (Pa)
THORIUM (Th)
ACTINIUM (Ac)
RADIUM (Ra)
FRANCIUM (Fr)
RADON (Rn)
ASTATINE (At)
POLONIUM (Po)
BISMUTH (Bu)
LEAD (Pb)
235U TO 207Pb SERIES
NUMBER OF PROTONS
NUMBER OF NEUTRONS


URANIUM (U)
PROTACTINIUM (Pa)
THORIUM (Th)
ACTINIUM (Ac)
RADIUM (Ra)
FRANCIUM (Fr)
RADON (Rn)
ASTATINE (At)
POLONIUM (Po)
BISMUTH (Bi)
LEAD (Pb)
238U TO 206Pb SERIES
NUMBER OF PROTONS
NUMBER OF NEUTRONS

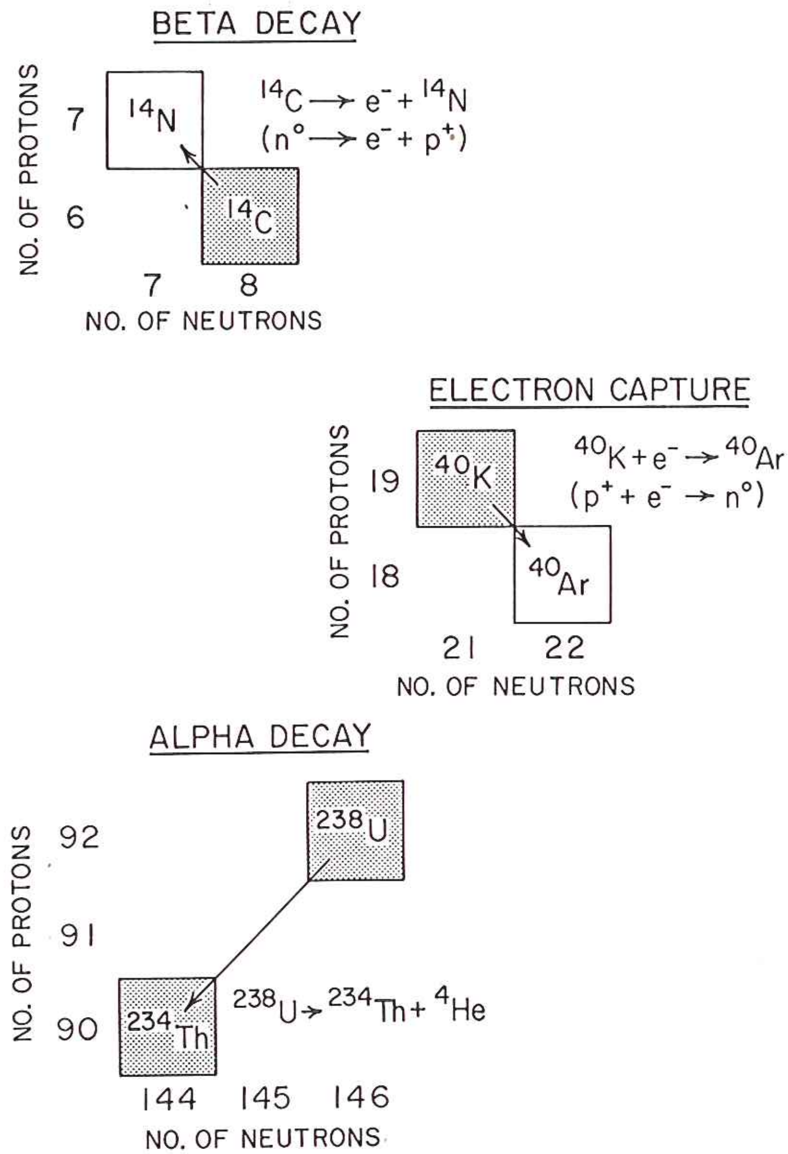


Figure 2-3. Examples of the three most common modes of spontaneous radioactive decay: Two of these, beta decay and electron capture, are isobaric—i.e., the number of nucleons remains the same. The third, alpha decay, involves the ejection from the nucleus of four particles in the form of a ^4He nucleus.

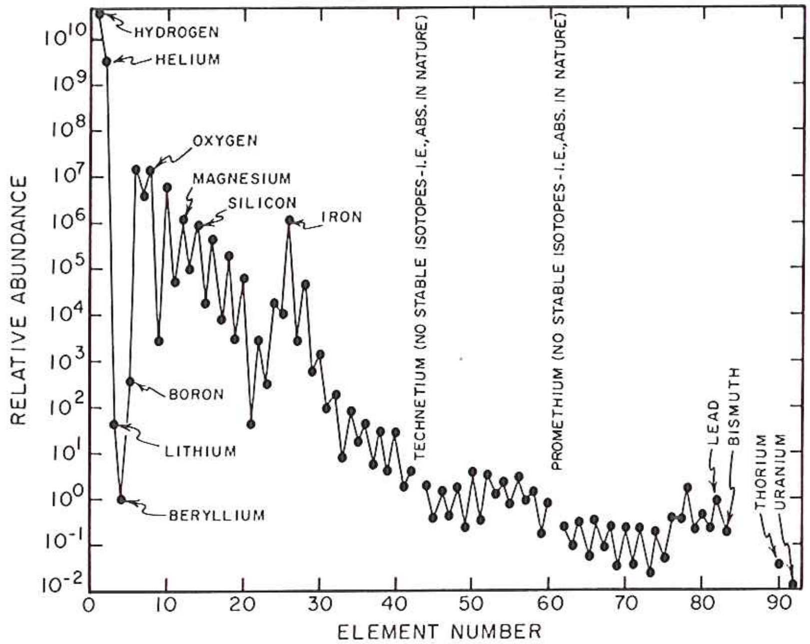


Figure 2-1. Relative abundances of the elements in our Sun: As the abundances range over 13 orders of magnitude, they must be displayed on a power-of-10 scale. The abundance of each element is expressed as the number of atoms per million (i.e., 10^6) atoms of the element silicon. The gaps in the sequence represent elements that have only radioactive isotopes and are, therefore, absent in the Sun. While most of the abundances are based on spectral data, use is made also of chemical measurements on a special class of meteorites called carbonaceous chondrites.

TABLE 1-7

Cosmic Abundances of the Elements (Atoms/10^6Si)

1	H	2.72×10^{10}	24	Cr	1.34×10^4	48	Cd	1.69	72	Hf	0.176
2	He	2.18×10^9	25	Mn	9510	49	In	0.184	73	Ta	0.0226
3	Li	59.7	26	Fe	9.00×10^5	50	Sn	3.82	74	W	0.137
4	Be	0.78	27	Co	2250	51	Sb	0.352	75	Re	0.0507
5	B	24	28	Ni	4.93×10^4	52	Te	4.91	76	Os	0.717
6	C	1.21×10^7	29	Cu	514	53	I	0.90	77	Ir	0.660
7	N	2.48×10^6	30	Zn	1260	54	Xe	4.35	78	Pt	1.37
8	O	2.01×10^7	31	Ga	37.8	55	Cs	0.372	79	Au	0.186
9	F	843	32	Ge	118	56	Ba	4.36	80	HG	0.52
10	Ne	3.76×10^6	33	As	6.79	57	La	0.448	81	Tl	0.184
11	Na	5.70×10^4	34	Se	62.1	58	Ce	1.16	82	Pb	3.15
12	Mg	1.075×10^6	35	Br	11.8	59	Pr	0.174	83	Bi	0.144
13	Al	8.49×10^4	36	Kr	45.3	60	Nd	0.836	90	Th	0.0335
14	Si	1.00×10^6	37	Rb	7.09	62	Sm	0.261	92	U	0.0090
15	P	1.04×10^4	38	Sr	23.8	63	Eu	0.0972			
16	S	5.15×10^5	39	Y	4.64	64	Gd	0.331			
17	Cl	5240	40	Zr	10.7	65	Tb	0.0589			
18	Ar	1.04×10^5	41	Nb	0.71	66	Dy	0.398			
19	K	3770	42	Mo	2.52	67	Ho	0.0875			
20	Ca	6.11×10^4	44	Ru	1.86	68	Er	0.253			
21	Sc	33.8	45	Rh	0.344	69	Tm	0.0386			
22	Ti	2400	46	Pd	1.39	70	Yb	0.243			
23	V	295	47	AG	0.529	71	Lu	0.0369			

Anders and Ebihara (1982).

Solar abundances:

- Sun dominated by H and He

  H : 30,000 × Si
  He : 2,000 × Si

i.e. He / H = 1/16 — 16 times as much H as He
by weight : He / H ≈ 25 %

- general decline in abundance with increasing Z

- paucity of Be, Li, B

- peak near Fe

- even – odd alternation (elements with <u>even</u> Z or <u>even</u> A more abundant than elements with <u>odd</u> Z or <u>odd</u> A)

- α – particle nuclides ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca show increased abundance

Nuclear binding energy:

$E = mc^2$ — Einstein

c = speed of light $= 3 \cdot 10^8$ m/sec

Generally measured in MeV $= 1.6 \cdot 10^{-13}$ J

Example: ^4He — 4.003 amu

Constituent parts: $2p + 2n + 2e^-$

$$2(1.0076 + 1.0090 + 0.00055) = 4.034 \text{ amu}$$

Binding energy of ^4He:

$$(4.034 - 4.003 \text{ amu})(1.67 \cdot 10^{-27} \text{ kg/amu})(3 \cdot 10^8 \text{ m/sec})^2$$

$$E = 4.7 \cdot 10^{-12} \text{ J} = 29 \text{ MeV}$$

In general: $1 \text{ amu} \times c^2 = 931$ MeV

^4He has 4 nucleons

Binding energy per nucleon: 7 MeV/nucleon

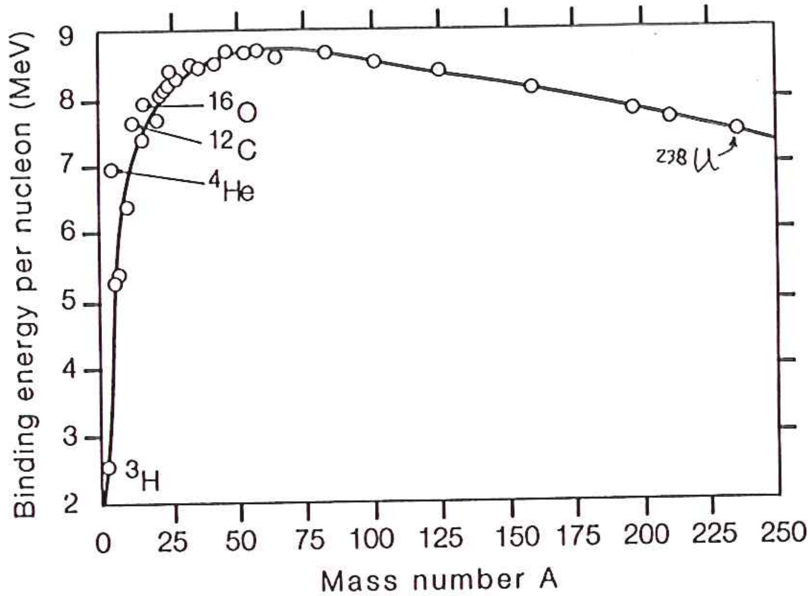


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

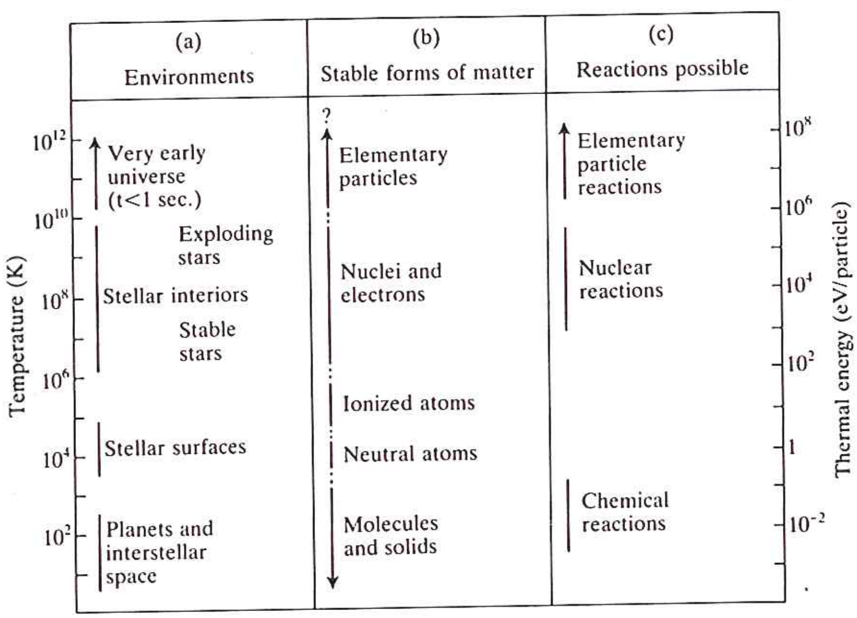


Fig. 1.9. Energy and temperature scales for chemical and nuclear processes. The scale on the left shows temperature, and that on the right indicates the average thermal energy for the particles present. Column (a) shows typical environments with different temperatures; (b) shows the stable forms of matter present; (c) indicates the types of reaction possible.

The Big Bang:

Although the very early stages are still uncertain, the picture becomes much clearer after the point where matter as we know it could form. After 1 second, the universe was composed of more familiar particles—protons, neutrons, electrons, neutrinos, and photons. Free neutrons would still be present in equilibrium at these temperatures, although they would soon start to undergo β^- decay into protons, electrons, and antineutrinos:

$$n = p^+ + e^- + \bar{\upsilon}. \tag{3.3}$$

As the temperature fell to around 10^9 K, more complex nuclei could start building up, by processes of fusion and neutron capture. The most important reactions, which were completed in a few minutes, were:

$$p + n = {}^2H + \gamma \tag{3.4}$$

$${}^2H + {}^2H = {}^3H + p \tag{3.5}$$

$${}^2H + {}^2H = {}^3He + n \tag{3.6}$$

$${}^3He + n = {}^4He + \gamma \tag{3.7}$$

$${}^3H + p = {}^4He + \gamma \tag{3.8}$$

Under the conditions present, it was certainly the first of these reactions—the formation of deuterons (^2H)—that constituted the rate-limiting step. This is because of the rather low binding energy of deuterons (2.2 MeV), so that they would be dissociated almost as rapidly as they formed. The remaining reactions occurred rapidly, and ^4He was by far the major product. The proportions of deuterium and ^3He remaining from this early stage of nucleosynthesis are very sensitive functions of the density of matter and so are a useful indicator of the conditions present at that time. On the other hand, the amount of helium produced depends less strongly on the density, and is largely determined by the equilibrium ratio of neutrons to protons at the temperature when the nuclear reactions can begin. Calculations predict a He/H atomic ratio of nearly 1:10, or about 25 per cent helium by weight. This is the abundance observed in stars, and is one of the strongest pieces of evidence that the big bang theory is correct.

1/16

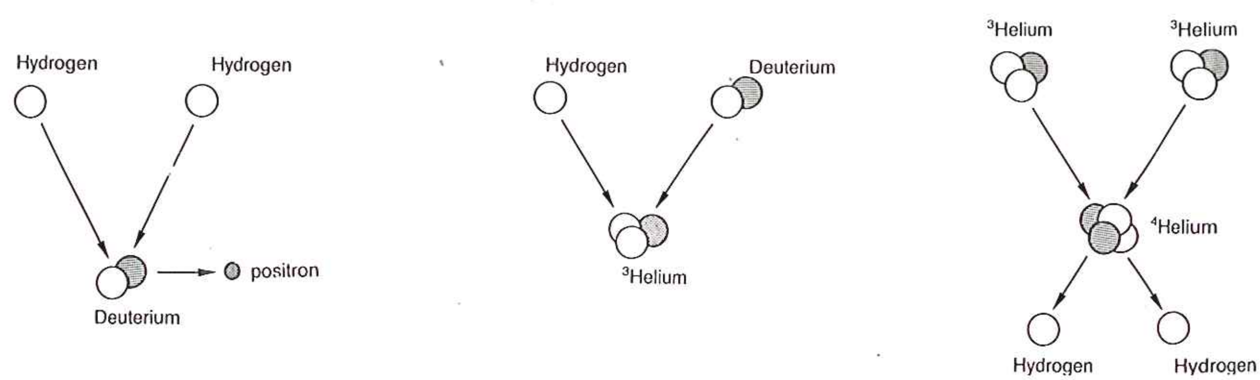


Figure 2.2

Hydrogen burning, the proton-proton chain, is an important energy-producing nuclear reaction that takes places inside stars like our Sun. In this process two hydrogen (H) nuclei combine to form a deuterium (D, hydrogen with an atomic weight of 2) nucleus and a positron (electron with a positive charge). Neutrons are shaded; protons are white. Reaction with an additional hydrogen nucleus produces a helium nucleus with a mass of three (^3He). The fusion of two such nuclei results in the production of stable helium (^4He, which has two protons) and the ejection of two hydrogen nuclei, which can be consumed in other reactions of this sort. Energy is released by these reactions as a small amount of matter is converted into energy in accordance with Einstein's equation, E (energy) = m (mass converted to energy) c^2 (the speed of light squared).

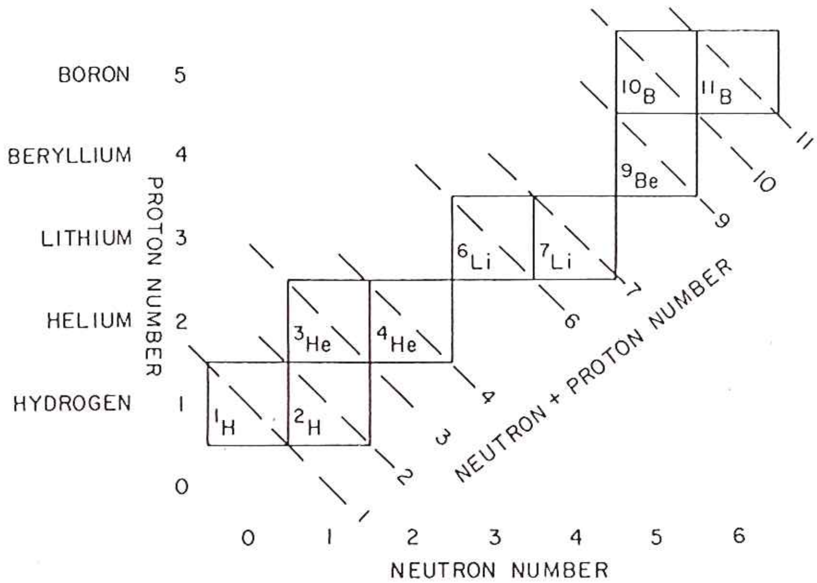


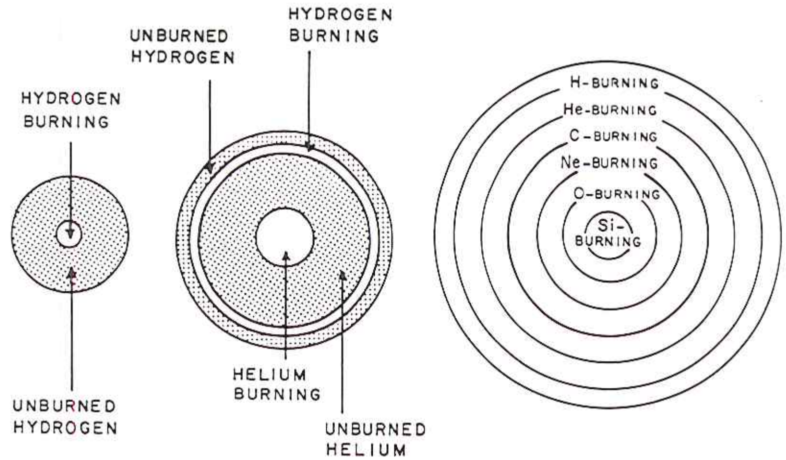
Figure 2-4. Stable nuclides with a particle number in the 1-to-11 range: Note that no stable nuclide exists with neutron-plus-proton number totaling 5 or 8. It is these two gaps in the chain that prevented element formation during the big bang from continuing beyond helium.

No stable nuclides with $A = Z + N = 5$ or 8

Both ^5He and ^5Li highly unstable
$T_{1/2} \approx 10^{-21}$ secs

Thus, three minutes after $t = 0$, the Universe consisted of H and He in ratio He/H = 25% by weight, and no other elements

All heavier elements are synthesized in <u>stars</u>



Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60 × 10^6 °K
Helium-Burning	He	C, O	200 × 10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800 × 10^6 °K
Neon-Burning	Ne	O, Mg	1500 × 10^6 °K
Oxygen-Burning	O	Mg to S	2000 × 10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000 × 10^6 °K

Figure 2-5. Three stars with progressively hotter nuclear fires: Like our Sun, the star at the left burns hydrogen to form helium in its core; this core is surrounded by unburned fuel. The middle star is burning helium to form carbon and oxygen in its core. This core is surrounded by a layer of unburned helium. Outside of this is a layer in which hydrogen burns to produce helium. Finally there is an outer layer of unburned hydrogen. The star on the right has a multilayered fire. The successive nuclear fires are separated by layers in which no reaction occurs. These layers contain the same fuel as is being consumed in the underlying fire. These layers are depleted in the ingredient being consumed in the overlying fire. The approximate temperatures required to ignite the successive fuels are also given.

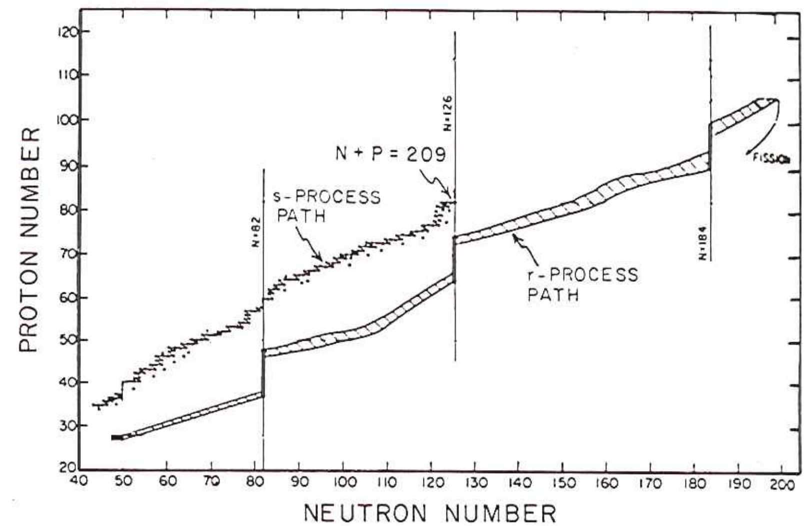


Figure 2-6. The elements heavier than iron were built by neutron irradiation: Two quite different processes contributed to this production. One, the s-process (i.e., slow process), occurs concurrently with the production of iron in the stellar core. As in a nuclear reactor, the reaction proceeds in a controlled way. Neutron hits are spaced out in such a way that the nuclides have time to achieve stability through beta decay. Thus, the buildup path follows the belt of stability shown in Figure 2-2. For the same reason it terminates at ^{209}Bi, the heaviest stable nuclide.

The r-process (i.e., the rapid process) occurs during the supernova explosion. Thus, it is akin to an atomic bomb. No sooner has a nuclide absorbed one neutron than it is hit by another. No time exists between hits for radiodecay. Rather, radiodecay occurs only when the nuclide becomes so neutron-rich that it cannot absorb any more. This leads to a buildup path displaced from the stability belt as shown. It also allows the buildup to proceed beyond particle number 209. Instead, the buildup goes just beyond particle number 300. At this point the colliding neutrons cause the nuclides to fission. The jogs in the r-process pathway occur at the so-called magic neutron numbers, 82, 126, and 184. They are "magic" in the sense they give the nuclide unusual stability.

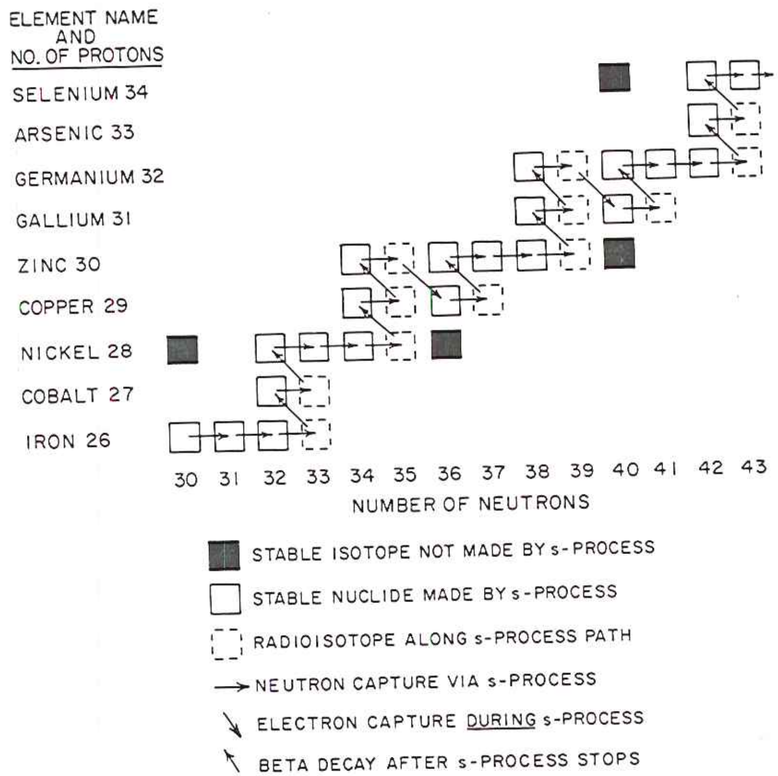


Figure 2-8. Details of the s-process path: Each time neutron capture produces a radioactive isotope, radiodecay occurs changing either a neutron into a proton or a proton into a neutron. Not all of the stable isotopes found in solar-system matter can be produced in this way. Those stable isotopes lying below the s-path are produced by the r-process. Those stable isotopes lying above the s-path are produced by proton bombardment.

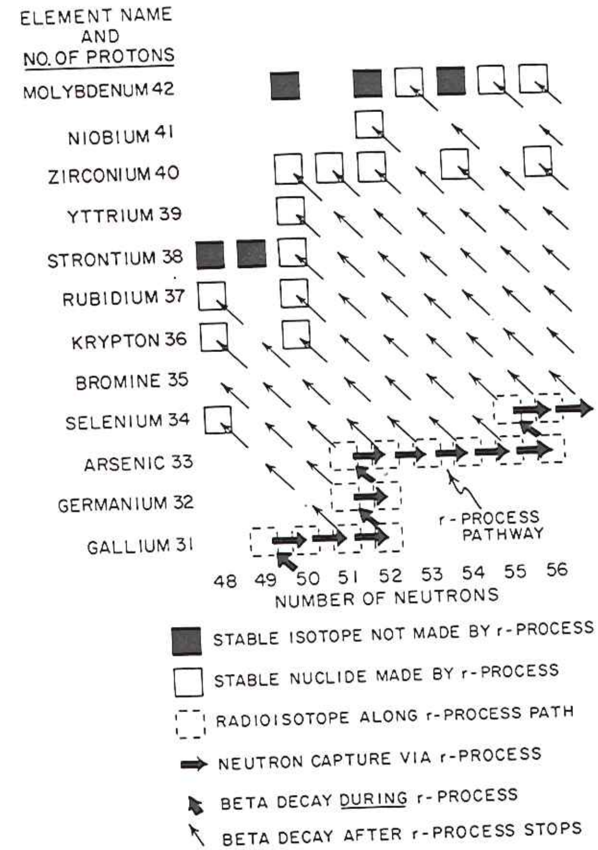


Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

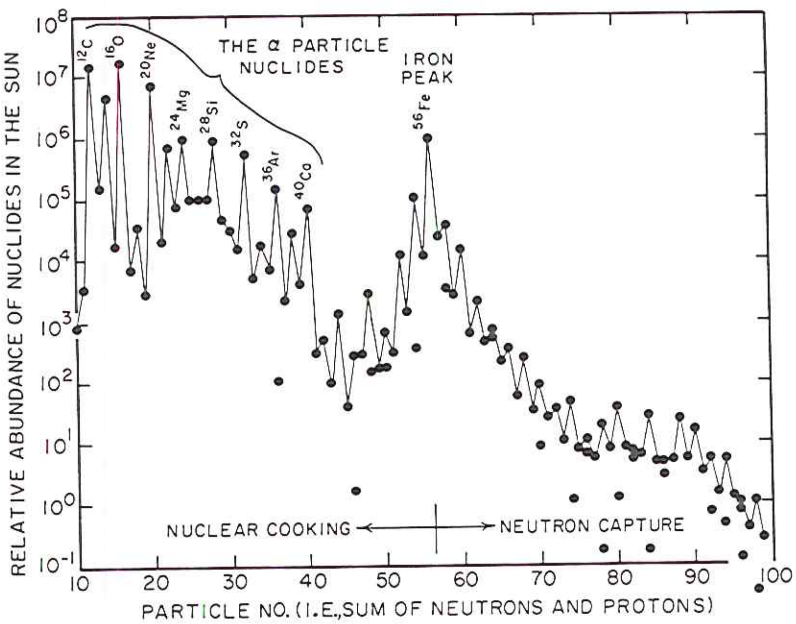


Figure 2-10. Relative abundances of individual nuclides: In the mass range 10 to 50, nuclides with particle numbers divisible by 4 (i.e., 12, 16, 20, 24, 28, 32 . . .) have abundances far above those of their neighbors. They are referred to as the α-particle nuclides. In the particle number range 50 to 100 the abundances of nuclides with an even particle number stand about a factor of 3 above those for their odd-numbered neighbors. Where more than one point is shown at a given mass number, two different nuclides with the same neutron-plus-proton number exist.

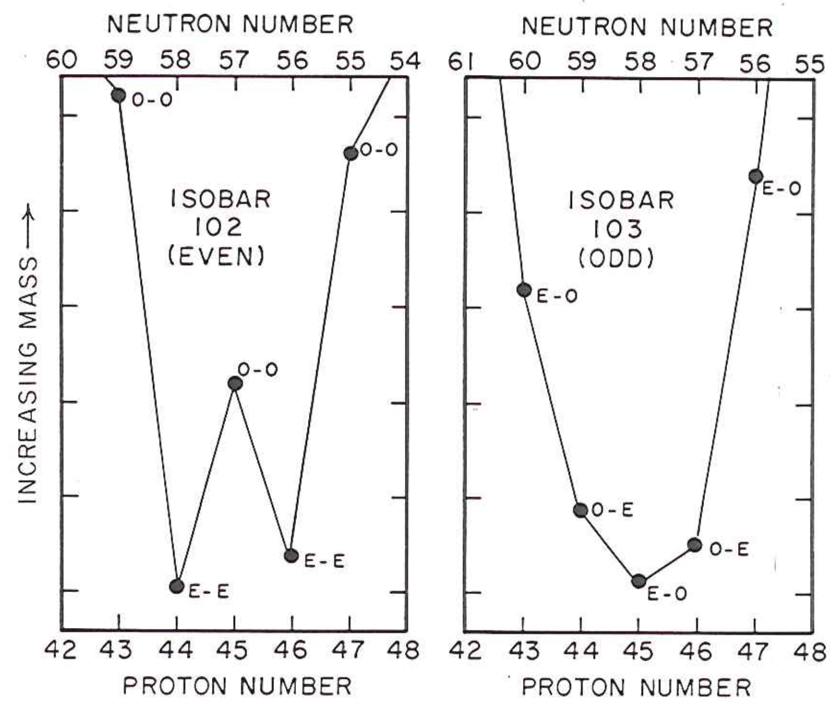


Figure 2-14. Odd–even particle number systematics: Shown here are the masses for two sets of nuclides. On the left are shown nuclides of particle number 102 (an even number). On the right are shown nuclides of particle number 103 (an odd number). The smaller the mass the more strongly the nuclide is bound together. For odd isobars, of the various possible neutron–proton combinations, one always has a lower mass than both its adjacent neighbors. For even isobars, there are usually two such nuclides. The reason for this difference is that odd–odd neturon–proton combinations are less tightly bound than even–even combinations.

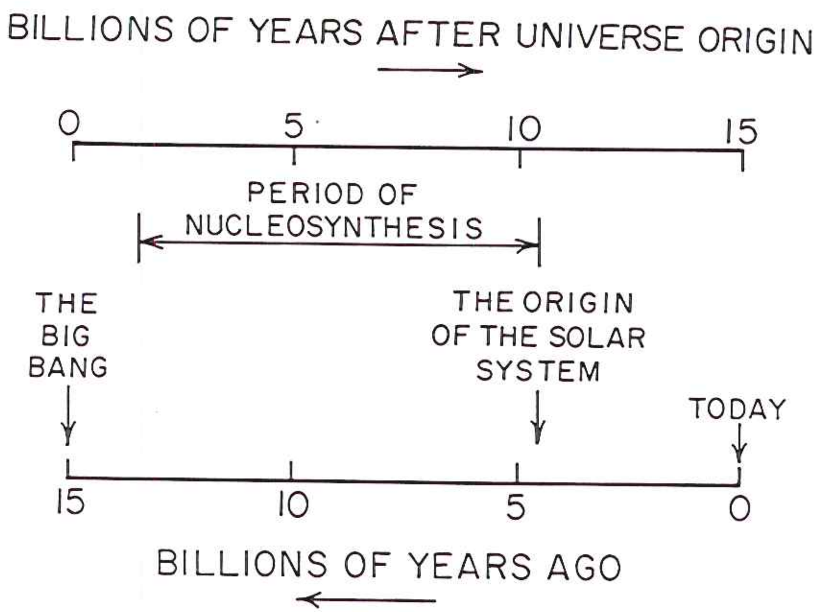


Figure 4-7. Summary of the chronology of universe events: The period of nucleosynthesis refers to the time interval over which the elements heavier than hydrogen and helium that are found in our solar system were produced. For the galaxy as a whole the period of nucleosynthesis extends right up to the present. The matter in the solar system was isolated from the galaxy 4.6 billion years ago.

Table 3-7. Relative abundance of the first 28 elements and their fates during the formation of the terrestrial planets:

Element Number	Element Name	Compound Solid	Compound Gas	Rel. Abundance In Sun*	Fate†	Rel. Abundance In Chondrites*
1	HYDROGEN		H_2	40,000,000,000	(1)	—
2	HELIUM		He	3,000,000,000	(1)	trace
3	LITHIUM	Li_2O		60	(3)	50
4	BERYLLIUM	BeO		1	(3)	1
5	BORON	B_2O_3		43	(2)	6
6	CARBON		CH_4	15,000,000	(1)	2,000
7	NITROGEN		NH_3	4,900,000	(1)	50,000
8	OXYGEN		H_2O**	18,000,000	(2)	3,700,000
9	FLUORINE		HF	2,800	(1)	700
10	NEON		Ne	7,600,000	(1)	trace
11	SODIUM	Na_2O		67,000	(2)	46,000
12	MAGNESIUM	MgO		1,200,000	(3)	940,000
13	ALUMINUM	Al_2O_3		100,000	(3)	60,000
14	SILICON	SiO_2		1,000,000	(3)	1,000,000
15	PHOSPHORUS	P_2O_5		15,000	(3)	13,000
16	SULFUR	FeS	H_2S	580,000	(2)	110,000
17	CHLORINE		HCl	8,900	(1)	700
18	ARGON		Ar	150,000	(1)	trace
19	POTASSIUM	K_2O		4,400	(2)	3,500
20	CALCIUM	CaO		73,000	(3)	49,000
21	SCANDIUM	Sc_2O_3		41	(3)	30
22	TITANIUM	TiO_2		3,200	(3)	2,600
23	VANADIUM	VO_2		310	(3)	200
24	CHROMIUM	CrO_2		15,000	(3)	13,000
25	MANGANESE	MnO		11,000	(3)	9,300
26	IRON	FeO,FeS,Fe		1,000,000	(3)	690,000
27	COBAL	CoO		2,700	(3)	2,200
28	NICKEL	NiO		58,000	(3)	49,000

*Relative to 1,000,000 silicon atoms.
†(1) Highly volatile; mainly lost;
(2) Moderately volatile; partly captured;
(3) Very low volatility; largely captured.
**Plus metal oxides.

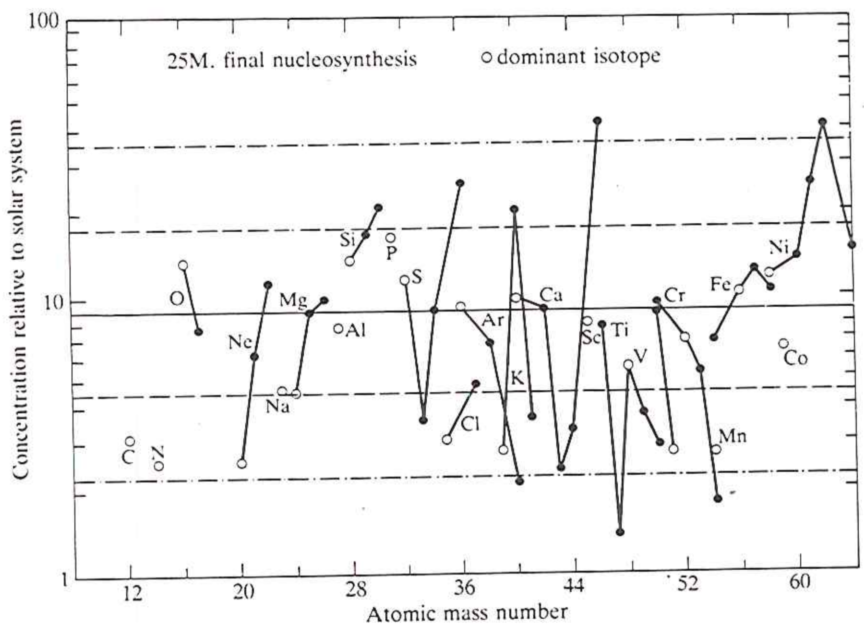


Fig. 3.5. Calculation of the elements produced by a supernova in a star of 25 solar masses. (From Woosley and Weaver 1986.) The predicted concentration of each nuclide has been compared with its observed solar system abundance. The calculation suggests that about one part in nine of the material forming the solar system has been produced by such supernovae.

Table 3-8. Isotopic abundances of the big four planet-producing elements:* Note that for three of the elements the dominant isotope has a nucleus consisting of an integral number of α-particles (i.e., four in ^{16}O, six in $^{24}M_6$, seven in ^{28}Si). The terrestrial planets are 85 percent by weight ^{16}O, ^{24}Mg, ^{28}Si, and ^{56}Fe!

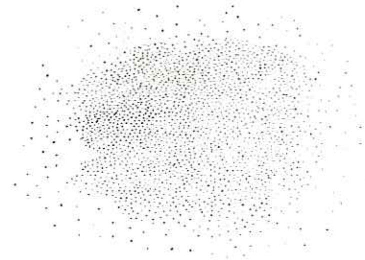
OXYGEN (8 protons)	^{16}O 99.76%	^{17}O 0.04%	^{18}O 0.20%	
MAGNESIUM (12 protons)	^{24}Mg 78.99%	^{25}Mg 10.00%	^{26}Mg 11.01%	
SILICON (14 protons)	^{28}Si 92.23%	^{29}Si 4.67%	^{30}Si 3.10%	
IRON (26 protons)	^{54}Fe 5.8%	^{56}Fe 91.8%	^{57}Fe 2.1%	^{58}Fe 0.3%

*In reading the lines in solar rainbows we get estimates of the abundances of elements. Many elements have more than one isotope. Thus the solar evidence must be supplemented if we are to get the abundances of individual isotopes. This is done by measuring the ratios of the isotopes of a given element in meteorites or Earth surface materials. Although separations among the elements have caused large biases in the chemical composition of Earth surface rocks, these separations do not extend to the isotopes of a given element. The isotopes of an element are nearly chemically identical. Thus, the isotopic composition of a given element is generally found to be the same whether the sample analyzed is from the Earth or from a meteorite.

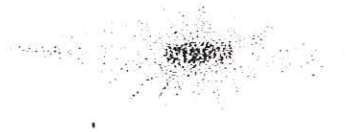
$\oplus \approx MgO + SiO_2 + \frac{1}{2} Fe_2O$
oxide composition of the Earth

TABLE 2-2
Simple Earth Model Based on Cosmic Abundances

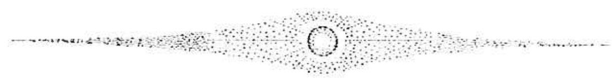
Oxides	Molecules	Molecular Weight	Grams	Weight Fraction
MgO	1.06	40	42.4	0.250
SiO_2	1.00	60	60.0	0.354
Al_2O_3	0.0425	102	4.35	0.026
CaO	0.0625	56	3.5	0.021
Na_2O	0.03	62	1.84	0.011
Fe_2O	0.45	128	57.6	0.339
Total			169.7	1.001



(A) **A slowly rotating portion of a large nebula** becomes a distinct globule as a mostly gaseous cloud collapses by gravitational attraction.



(B) **Rotation of the cloud prevents collapse of the equatorial disk** while a dense central mass forms.



(C) **A protostar "ignites"** and warms the inner part of the nebula, possibly vaporizing preexisting dust. As the nebula cools, condensation produces solid grains that settle to the central plane of the nebula.

(D) **The dusty nebula clears** either by dust aggregation into larger particles (planets or planetesimals) or by ejection during a T-Tauri stage of the star's evolution. A star energized by fusion and a system of cold bodies remains. Gravitational accretion of these small bodies eventually leads to the development of a small number of major planets.

Figure 2.6

The evolution of a dusty nebula with a surrounding system of orbiting planets is shown in this schematic diagram.

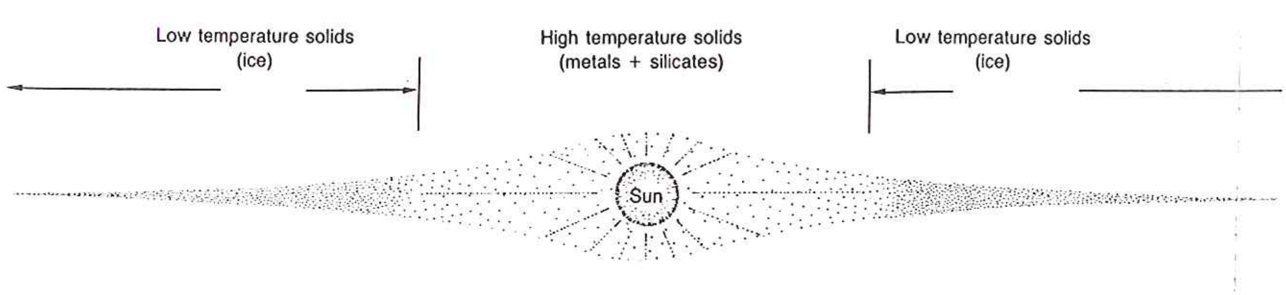


Figure 2.8

A cross section of a hypothetical nebula shows a star forming in its center. Condensation of solids from a solar nebula with a temperature gradient may have given rise to compositional differences in the condensates. At one instant, the condensates in the inner part of the developing solar system would consist of high temperature materials such as silicates, while at the same instant, but farther from the Sun, the nebula may have been cool enough to allow ices to be fully condensed as well. Since water was relatively abundant in the nebular gases, more solid matter formed in the cooler outer part of the nebula.

extra