

Nuclear Astrophysics



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The Central Question of Nuclear Astrophysics:

How did the stuff our solar system and humans are made of come to be?

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How did the stuff our solar system and humans are made of come to be?

Also:

- How do the stars shine?
- How do stars explode?
- What are neutron stars?

The abundances of isotopes in our solar system



Moment of Big Bang

Schematic diagram showing development of the universe in space and time



Planck Era We tack a theory to describe conditions in the Planck era	TIME 77	TEMPERATURE
GUT Era Two forces are thought to hav operated during the GUT eral gravity and the GUT force.	• ?	
Electroweak Era Elementary particles appears spontaneously from energy b a so transformed rapidly back into energy.	Time (by powers of 10)	- 10- K
	TIME	1015 4
Particle Era Elementary particles filed the universe, then quarks combined to make protons and antiprotons.		- 10 - A-
Era of Nucleosynthesis Fusion produced helium from protons (Hinuclei).		-10 ^w K
Era of Nuclei A plasma of free electons and H and He nuclei filled the universe.	5 min-	- 10 ⁹ K
Era of Atoms The err of alone, asced until e and galaxies began to form.	100 yr - etans	- 3000 K
	.	
Key • electron Santiproton • antie ectron Return • neutrino Santineutron • antineutrino I definition § quarks Signation photon		~

TEMPERATURE



Era of Nucleosynthesis

Began ~0.001 second after Big Bang when universe became too cool to produce protons and neutrons

Cooling allowed protons and neutrons to fuse into long-lasting He





10^{12} K - 10⁹ K - 1

Era of Nucleosynthesis

Most of the helium now in the universe was made during this era.

Evidence: We can measure the amount of helium made during this era.

Era of Atoms The era of atoms lasted un and galaxies began to form

the universe.



			Key														
T H tycircgen 1 00794			1 Magri 24.)	2	Alom Elem Elem Alom	ic numb ent's syn ent's nan ic mass*	or Ibol Ie										2 He Hel um 4003
3 Li Lithium 6.941 11 Na Sodium 22.990	4 Be Deryflium 9.01218 12 Mg Magnes um 24.305	Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes— in proportion to the abundance of each isotope on Earth.												10 Ne Veon 20,179 18 Ar Argon 36,949			
19 K 20lassium 39.098	20 Ca Calcium 40.08	.21 Sc Standium 44,856	22 Ti Itanium 77,85	23 V Vanadium 50.94	24 Cr Otromium 51 996	25 Mn Manganose 54.938	26 Fe Iron 55 847	27 Co Cobal: 58/9332	28 Ni Nicko 55.69	29 Cu Copper 63.546	30 Zn 2inc 65.39	3* Ga Gal lum 69.72	3.2 Ge Germanium 72.59	33 As Arsonic 74.922	34 Se Splonium 78.96	25 Br Bromine 73.904	36 Kr Krypton 83.80
37 Rb Aubidium 85,463	38 Sr Strontium 87.62	39 Y Yttrium 88 9059	40 Zr 2rccrium 91,224	41 Nb Nobium 92.91	42 Mo Motybdenum 95.94	43 Tc lechnetium (96)	44 Ru Ruthenium 101.07	45 Rh Phodium 102,906	46 Pd -alladium 106.42	47 Ag Silver 107.868	48 Cd Gadm um 112,41	19 In Inclum 11482	50 Sn 118 11871	51 Sb Antimony 121.75	52 Te 1::llurium 1:27.60	53 odine 26,905	54 Xe Xenon 131,29
55 Cs Cesium 132301	56 Ba Barium 137.34		72 Hf Ilahrum 178,49	73 Ta Tantalum 180.65	74 W Turtuster 183.85	75 Re Eterium 186 207	76 Os Danium 1907	77 Ir Iridium 192.32	78 Pt Platinum 195-38	79 Au Gold 190.967	80 Hg Mercury 20059	81 Ti Thallium 204,383	82 Pb Lead 207.2	63 Bi Bismuth 208.96	84 Po Potonium (209)	85 At Astatine (210)	86 Rn 3adon (292)
87 Fr Frandum (223)	88 Ra Rad un: 226,0254		104 Rf flut e fordium (263)	106 Db Dubri um (282)	106 Sg Ssaborgium (296)	107 Bh Bohrium (267)	108 HS flassum (277)	109 Mt Mei nerium (260)	10 Ds Demotadium (261)	111 Rg Roentgemum (272)	1 12 Cn Copernicium (285)	113 Uut Urientrium (294)	14 Uuq Durcuacion (209)	115 Uup Drunpentium (288)	116 Uuh Uriur hexium (292)	117 Uus Ununseptiur (294)	118 Uuo 10nuroctium (294)
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			57 La Lantranum 138.905	56 Ce Cetiuni 140.12	59 Pr Prasecoymium 140,908	60 Nd Neodymium 14424	61 Pm Fromethium (145)	62 Sm Samar um 150.35	63 Eu Europium 151.96	64 Gd Gadolirium 167,25	56 Tb Terbium 162.925	66 Dy Dysprosium 162.50	67 Ho Iolinium 164.98	68 Er Erbium 167.25	69 Tm Trollum 168,984	70 Yb Ytterbium 173.04	71 Lu Lutetium 174,367
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Big Bang made 75% H, 25% He.

First, lets think about how stars shine



Radius:

6.9 x 10⁸ m (109 times Earth)

Mass: 2 x 10³⁰ kg (300,000 Earths)

Luminosity: 3.8 x 10²⁶ watts (3.8 x 10²⁶ J/s)

The Sun

power = energy time

Iuminosity =power output in formof radiative energy

Lifetime = Total Energy Stored luminosity

Sun's Energy Content

Chem. energy = 4×10^{38} J (~ 30,000 yr)

Grav. energy = 4×10^{41} J (~ 30 million yr)

Nuclear energy = 1×10^{45} J (~ 100 billion yr)*

Mass-energy = 2×10^{47} J (~ 10 trillion yr)

The sun can live in an unchanging state for about 10 billion years burning hydrogen to helium in its core. Currently, the sun is about 5 billion years old.This burning is not so interesting for nucleosynthesis since it is only producing already abundant helium.



Fission

Fusion

Big nucleus splits into smaller pieces.

Small nuclei stick together to make a bigger one.

(Nuclear power plants) (Sun, stars)

In both cases, the mass of the initial system is more than the total mass of the final system, so energy is released.



High temperatures enable nuclear fusion to happen in the core of a star.





The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

Total mass is 0.7% lower -> Energy Released

The **Proton–proton chain** is how hydrogen fuses into helium in the Sun. Figured out by Bethe 1937, Nobel prize in 1967.

What happens when the hydrogen runs out?



- No more energy is released from nuclear burning in the core, so core loses pressure support and begins to contract
- The core heats up due to contraction and eventually ignites a new fuel (and hydrogen burning may begin in a shell outside of the core)

What Happens When the Hydrogen Runs Out?



- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion larger charge leads to greater repulsion.
- The fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon.



Life Stages of a Low-Mass Star

- **1.** *Main Sequence:* H fuses to He in core.
- **2.** *Red Giant:* H fuses to He in shell around He core.
- **3.** Helium Core Fusion: He fuses to C in core while H fuses to He in shell
- **4. Double Shell Fusion:** H and He both fuse in shell.
- Planetary Nebula: leaves white dwarf behind

Not to scale!

			Key														
1 H Hydrogen 1.00794		12 Atomic number Mg Element's symbol Msgres un Element's name 24.305 Atomic mass*												2 He un 4.003			
3 Li Lithium 6.941 11 Na Sodium 22.990	4 Be Beryllium 9.01218 12 12 Mg Magnes um 24.305	SBCNOFMathematical average of atomic masses of different isotopes— in proportion to the abundance of each isotope on Earth.1314151817AlSiPSClMumhumSilconSilconSulfurSulfurSulfurSulfur26.9828.05630.97432.0635.453												10 Ne Veon 20.179 18 Ar 4rgon 36.948			
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			Lanthan	ide Ser	ties	C.P.	24	63	67	64	26	66	67	60	50	70	74
			La Lantranum 138.905	Ce Cetiuni 140.12	Pr Praseocymium 140,908	Nd Neodymium 14424	Pm Promethium (145)	Samar um 150.35	Eu Europium 151.96	Gd Gədəliriun 167,25	Tb Tercium 153.925	Dy Dysprosium 162.50	Ho Halmium 164.93	Er Erbium 167.26	Tm Thulium 168.984	Yb Ytterbium 173.04	Lu Lutatium 174367
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Helium fusion can make carbon in low-mass stars like the sun, but that is about it.

What happens in more massive stars?

Helium Capture



 High core temperatures in more massive stars allows helium to fuse with carbon.

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1 H Hydrogen 1.00794			1 Magro 24,3	2	Atom Elem Elem Atom	ic numbo ent's sym ent's nan ic mass*	or Ibol ne										2 He Helium 4.003
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39.098	40.08	44,556	17.85	50.94	51 996	54 938	35 847	58.9332	58.69	63.546	65.59	69.72	72.59	74.922	78.96	73.904	83.80
37 Dh	33	39	40	41	42	43	44	45	46	47	48	43	50	51 Ch	52	53	54
HD Bubidium	Strontium	Yttri, m		ND	IVIO Noboleniim	I C lechnetium	Ruthenium	-hoch m	-alladium	Ag	Cadm um	Inclum	Sn	Antimony	ielurium.	l lodice	Xenop
95.469	87.62	88 9059	91,224	92.91	95.94	(96)	101.07	02.906	106.42	107.868	112,41	1 4 82	118.71	121.75	27.60	126,905	131.29
55	56		72	73	74	75	76	77	78	79	-80	8	82	63	84	28	86
Cs	Ba	1	Ht	Та	W	Re	Os	Ir	Pt	Au	Hg	TI	Pb	BI	Po	At	Rn
132.91	137.34		178.40	180.65	183.85	186.207	190.2	192.32	195.08	196.967	200.59	204,383	207.2	208.98	(209)	(210)	(292)
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			57 La La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	66 Tb Techium	66 Dy	67 Ho	68 Er	69 Tm Tradi on	70 Yb	71 Lu
			57 La Latranom 138.905	58 Ce Cetiuni 140.12	59 Pr Præsoymium 140.008	60 Nd Neodymium 14424	61 Pm Promethium (145)	62 Sm Samar um 150.35	63 Eu Europium 151.96	64 Gd Gadolirium 157.25	56 Tb Tercium 153.925	66 Dy Dysprosium 162.50	67 Ho Jahrium 164,93	68 Er Ertium 167.26	69 Tm Trolium 168,984	70 Yb Ytterbium 173.04	71 Lu Lutatium 174.367
			Lanthan 57 La La Latranun 132.905 Actinide	58 Ce Ce Ceiton 140.12 Series	59 Pr Pr 140,938	60 Nd Neodymium 14424	61 Pm Fromethium (145)	62 Sm Samar um 150.35	63 Eu Europium 151.96	64 Gd Gadulirium 157.25	56 Tb Tercium 153.925	66 Dy Dysprosium 162.50	67 Ho Halirium 64.93	68 Er Erbium 167.26	69 Tm Trulium 158.994	70 Yb Yttarbium 173.04	71 Lu Lutsium 174.367
			Lanthan 57 La La Latranon 132.905 Actinide 89	58 Ce Ceituni 140.12 Series 90	59 Pr Pr 140,938	60 Nd Neodymium 14424 92	61 Pm Promethium (145) 93	62 Sm Samar um 150.35	63 Eu Europium 151.96	64 Gd Gadulirium 157.25 96	96 Tb Teroium 153.925 97	66 Dy Dysprosium 162.50	67 Ho Jahrium 64.93	68 Er Ertium 157.26	69 Tm Tratium 158.984	70 Yb Ytterbium 173.04	71 Lu Lutsium 174.307
			Lanthan	56 Ce Ceium 140.12 Series 90 Th	59 Pr Pr 140.938	60 Nd Neodymium 14424 92 U	61 Pm Promethium (145) 93 Np	62 Sm Samar um 150.35 94 Pu	63 Eu Europium 151.96 95 Am	64 Gd Gadolirium 157.25 98 Cm	96 Tb Teroium 152.925 97 Bk	66 Dy Dysprosium 162.50 88 Cf	67 Ho Iolinium 64.93 99 Es	68 Er Erbium 167.26	69 Tm Tralium 158.994	70 Yb Ytterbium 173.04	71 Lu Lutaium 174:367 103 Lr
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Helium capture builds C into O

SUMMARY Advanced Nuclear Burning Stages (e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10 ⁹ K)	Time (yr)
Η	He	^{14}N	0.02	107
He	С,О	¹⁸ O, ²² Ne	0.2	106
		s- process		
C×	Ne, Mg	Na	0.8	10 ³
Ne	O, Mg	Al, P	1.5	3
0	Si, S	Cl, Ar	2.0	0.8
		K, Ca		
Si 📕	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week



• Advanced nuclear burning proceeds in a series of nested shells.

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1 H Hydrogen 1.00794		12 Atomic number Mg Element's symbol Magres un Element's name 24.325 Atomic mass*												2 He Hel um 4.003				
3 Li Lithium 6.941	4 Be Berytlium 9.01218	Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes— in proportion to the abundance of each isotope on Earth.													10 Ne Veon 20173			
Na Sodium 22.997	Mg Magnes um 24.315		13 14 5 18 17 AI Si P S CI Aluminum Silon Phosphoru Sulfur Chlorine 26.93 28.055 30.974 32.05 35.453										Ar Argon 30 949					
19 K Polassium 30.033	20 Ca Calcium	21 Sc Scandium 44,856	22 Ti Hanium 77.95	23 V Vanadium 50.94	24 Cr Otremium 51,996	25 Mn Manganose 54 938	26 Fe Iron 55.842	97 Co 00031 58,9322	28 Nicko 58.69	29 Cu Copper 63.546	30 Zn 2inc 65.39	3* Ga Gal lum 69.72	32 Ge Germanium 72,58	33 As Arsonic 74.922	34 Se Solenium 78.96	35 Br Bromine 73.904	36 Kr Kypton 83.80	
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Advanced reactions in stars make elements such as Si, S, Ca, and Fe.

Evidence for Stellar Nucleosynthesis



The abundances of nuclei in our solar system



Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)

What happens once you reach iron?



- Iron builds up in the core of massive stars until electron pressure can no longer resist gravity.
- The core then suddenly collapses, the released gravitational bindings energy powers a supernova explosion of the outer layers of the star and leaves behind a neutron star or a black hole.
- This explosion ejects nucleosynthesis products back into the interstellar gas
- Some of the largest explosions in the universe, energy release equivalent to 100 million billion billion billion (10³⁵) tons of TNT







The Crab Supernovae Remnant (SN occurred in 1054 AD)



Evidence for Stellar Nucleosynthesis



The abundances of nuclei in our solar system

Neutron Capture (N+1, Z) (N, Z) Same element, new isotope, usually unstable $\bar{\nu}_e$ eBeta Decay (N+1, Z) (N, Z+1)

New Element!

Two ways to capture neutrons

Slowly (s-process):

Capture a neutron and then beta-decay back to stability, then repeat. This process occurs during later stages of stellar burning as a secondary process, responsible for about half of the elements heavier than iron.

> Get neutrons from: ¹³C + ⁴He --> ¹⁶O + *n* ²²Ne + ⁴He --> ²⁵Mg + *n*





Rapidly (r-process):

Capture many neutrons before beta-decay and move far from stability. We know this must happen somewhere, but the exact site is uncertain. Need **lots** of free neutrons.

r-process flow



FRIB will help us understand the r-process path





Where can we get lots of neutrons? Neutron Stars!



A neutron star is about the same size as the Lansing area, but with a mass comparable to that of the sun.

Which of these objects has about the same mass as one cubic centimeter of neutron-star matter?



(~ 10⁹ g)

(~ 10¹² g)

(~ 10¹⁵ g)



Neutron Star Mergers

- Neutron stars in binaries spiral towards one another through gravitational wave emission
- Eventually tear one another apart, eject a little bit of material, and form either another more massive neutron star or a black hole.
- The material thrown out into space is very neutron rich, can undergo rapid neutron capture process

Advanced LIGO

Two years ago GW170817! Also saw light in coincidence with the GWs which was strong evidence that rprocess nuclei were produced in the ejecta

4 km

The Central Question of Nuclear Astrophysics:

How did the stuff our solar system and humans are made of come to be?

The Big Bang, Stars, Supernovae, Neutron star mergers...