Nuclear Astrophysics Theory: The Origin of the Elements

Maria Lugaro

Konkoly Observatory, Hungarian Academy of Sciences and Monash University, Australia

.

- These lectures are interactive, please expect to have to do something
- You can work in groups, talk with the others
- You can ask any question anytime!



Chemical Elements: The periodic table

Group	1	2						:					13	14	15	16	17	18
Period					=				004			Fel						
1	$\stackrel{1}{\mathrm{H}}$					N E J	60	_	IY	PT		Nd HB						2 He
2	3 Li	4 Be	Edu	catio	Ur nal, S	nited I Scient	Nation ific an	ns . Id .	Interi of the	nationa Perio	l Year dic Tab	le	5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	${{}^{12}_{{ m Mg}}}$		Cultural Organization · of Chemical Elements · Al Si P S Cl														18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	$\frac{40}{\mathbf{Zr}}$	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lantha	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb				
**Acti	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No				

Che	Chemical Elements: The periodic table															le		
Group Period	1	2	3	4	5	6	7	8	Ma	ade	e in	h th	e l	Big	Ba	ng	17	18
1	$\frac{1}{H}$)	E	3v	fai	[,] th			_	2 He								
2	3 Li	4 Be	e	ele	me	ent	s ir	n tł	5 B	6 C	7 N	8 O	9 F	10 Ne				
3	$\frac{11}{Na}$	$\stackrel{12}{\mathrm{Mg}}$							13 Al	14 Si	15 P	16 S	17 Cl	18 Ar				
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	$\frac{40}{\mathbf{Zr}}$	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	$\frac{108}{Hs}$	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
_			57	50	50	80	R1	60	62	64	85	88	67	60	60	70		
*Lanthanoids La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb																		
**Actinoids 89 90 91 92 93 94 95 96 97 98 99 100 101 102 **Actinoids Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No											102 No							



Bl

No

**Actinoids

Earth's crust abundances



Human Body Ingredients

The four ingredients below are essential parts of the body's protein, carbohydrate and fat architecture.



65.0% critical to the conversion of food into energy.



18.5%

The so-called backbone of the building blocks of the body and a key part of other important compounds, such as testosterone and estrogen.



HYDROGEN 9.5%

Helps transport nutrients, remove wastes and regulate body temperature. Also plays an important role in energy production.



NITROGEN

Found in amino acids, the building blocks of proteins; an essential part of the nucleic acids that constitute DNA.

(Percentage of body weight. Source: Biology, Campbell and Reece, eighth edition.)

Other Key Elements

Calcium 1.5%

Lends rigidity and strength to bones and teeth; also important for the functioning of nerves and muscles, and for blood clotting.

Phosphorus 1.0%

Needed for building and maintaining bones and teeth; also found in the molecule ATP (adenosine triphosphate), which provides energy that drives chemical reactions in cells.

Potassium 0.4%

Important for electrical signaling in nerves and maintaining the balance of water in the body.

Sulfur 0.3%

Found in cartilage, insulin (the hormone that enables the body to use sugar), breast milk, proteins that play a role in the immune system, and keratin, a substance in skin, hair and nails.

Chlorine 0.2% Needed by nerves to function properly; also helps produce gastric juices.

Sodium 0.2%

Mays a critical role in nerves' electrical signaling; also helps regulate the amount of water in the body.

Magnesium 0.1%

Plays an important role in the structure of the skeleton and muscles; also found in molecules that help enzymes use ATP to supply energy for chemical reactions in cells.

Iodine (trace amount) Part of an essential

hormone produced by the thyroid gland; regulates metabolism.

Iron (trace amount) Part of hemoglobin, which carries oxygen

in red blood cells.

Zinc (trace amount) Forms part of some enzymes involved in digestion.



To understand the origin of the chemical elements we need to understand how their **atomic nuclei** are created.

The Chart of Nuclei represents all the elements and nuclei in the Universe. Black boxes are stable nuclei.



The nuclide chart

								e: 100.00%				
N	umbe	er o	f			10N P: 100.00%	11N 1.58 MeV P: 100.00%	12N 11.000 MS	13N 9.965 M	14N STABLE 99.634%	15N STABLE 0.366%	7 8-1
	roton	SZ				1.100.00//	1.100.00/0	0.100.00/0	0.100.00//			β-α
T					8C 230 KeV	9C 126.5 MS	10C 19.290 S	11C 20.334 M	12C STABLE	13C STABLE	14C 5700 Y	2
					P: 100.00% et	€: 100.00% €p: 61.60%	e: 100.00%	e: 100.00%	30.03%	1.11%	β-: 100.00%	β-:
				6B	7B 1.4 MeV	8B 770 MS	9B 0.54 KeV	10B STABLE 19.8%	11B STABLE 80.2%	12B 20.20 MS	13B 17.33 MS	1
				2P	a P	εα: 100.00% ε: 100.00%	2a: 100.00% P: 100.00%			β-: 100.00% B3A: 1.58%	β-: 100.00%	β-: β-:
1				5Be	6Be 92 KeV	7Be 53.22 D	8Be 5.57 eV	9Be STABLE 100.%	10Be 1.51E+6 Y	11Be 13.81 S	12Be 21.49 MS	2.7
				Р	a: 100.00% P: 100.00%	€: 100.00%	a: 100.00%	100.00	β-: 100.00%	β-: 100.00% β-α: 3.1%	β-: 100.00% β-n≤ 1.00%	
		31	Li	4Li 6.03 MeV	5Li ≈1.5 MeV	6Li STABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS	9Li 178.3 MS	10Li	11Li 8.59 MS	<
			Р	P: 100.00%	P: 100.00% a: 100.00%			β-α: 100.00% β-: 100.00%	β-: 100.00% β-n: 50.80%	N: 100.00%	β-: 100.00% β-na: 0.027%	
				3He STABLE 0.000137%	4He STABLE 99,999863%	5He 0.60 MeV	6He 806.7 MS	7He 150 KeV	8He 119.1 MS	ЭHe	10He 300 KeV	
						N: 100.00% a: 100.00%	β-: 100.00%	Ν	β-: 100.00% β-n: 16.00%	N: 100.00%	N: 100.00%	
		11 STA 99.93	H BLE 85%	2H STABLE 0.015%	3H 12.32 Y	4H 4.6 MeV	5H 5.7 MeV	6H 1.6 MeV	7H 29E-23 Y			
			00/1	0.010/0	β-: 100.00%	N: 100.00%	N: 100.00%	N: 100.00%	2N?			
		0		Neutron 10.23 M								
				β-: 100.00%								
									•			

Number of neutrons N

What is the number of neutrons of the stable isotopes of C:



4. 12

What is the ¹²C/¹³C abundance ratio in the solar system:



What is the half-life of ^{13}N :



- 2. ~10 minutes
- 3. ~10 hours



What are stars made of?

NGC 6397 Hubble Space Telescope Image "We shall never be able by any means to study the chemical composition [of stars] or their mineralogical structure."

Auguste Comte *Cours de la Philosophie Positive*, 1835

What is the Solar System made of?



Each dark line corresponds to an atomic transition of an atom/ion of a specific chemical element.

Method 2. Analyse the composition of Extra-terrestrial rocks that formed when the Sun formed

Meteor, meteoroid, meteorite: What is the difference?



The Solar System abundances

Solar spectra + meteorites:



The Solar System abundances

Solar spectra + meteorites:



- No much He, C, N, O etc in meteorites (rock forming elements are there)
- It is impossible or very hard to obtain isotopic abundances from spectra

The abundances from solar spectra and meteorites show the features of nuclear physics!

Can you find these features in the figure?

1. Identify the peaks, which isotopes are they?

2. Why are these isotopes more abundant than others?
Hints: Remember (1) the magic numbers: 2, 8, 20, 28, 50, 82, and 126, and (2) the nuclei with the highest binding energy per nucleon

Nuclear shell model, closed shells = stability
 → magic numbers, apply to both *protons* and

neutrons



We can find *proton or neutron magic* and *double magic* nuclei on the nuclide chart

50

The binding energy per nucleon is the average energy needed to "break off" one nucleon from the nucleus.



The Solar System abundances

Solar spectra + meteorites:



- No much He, C, N, O etc in meteorites (rock forming elements are there)
- It is impossible or very hard to obtain isotopic abundances from spectra

The abundances from solar spectra and meteorites show the features of nuclear physics!

Can you find these features in the figure?

1. Identify the peaks, which isotopes are they?

2. Why are these isotopes more abundant than others? Hints: Remember the magic numbers: 2, 8, 20, 28, 50, 82, and 126, and which are the nuclei with the highest binding energy per nucleon...

The *nuclear physics* of the Solar System abundances



The nuclear physics of the Solar System abundances



Solar System abundances: nucleosynthesis





Margaret Burbidge turned 100 yesterday!



Prof. Margaret Burbidge consejoculturalmundial.org



E. Margaret Burbidge (1919-... flickr.com



E. Margaret Burbidge on Twitter: "I ... twitter.com



Astronomer Margar sandiegouniontribune



William Fowler with Geoffrey and ... archives-dc.library.caltech.edu



Wire Photo Professor Marg... outlet.historicimages.com





Emilio Segre Visual ... pixels.com

Solar System abundances: nucleosynthesis



Solar System abundances: nucleosynthesis



How do we know these processes happen in stars?

Spectroscopy in the 1950s...



Merrill 1952, Burbidge et al. 1957 Each line originates from absorption from a specific atomic transition in a specific atom/ion

Spectroscopy in the 1950s...



Merrill 1952, Burbidge et al. 1957

What is special about technetium (Tc)? Find this element on the nuclide chart!

What is special about technetium (Tc)? Find this element on the nuclide chart!

95Rh 5.02 M ≪ 100.00%	96Rh 9.90 M	97Rh 30.7 M < 100.00%	98Rh 8.72 M < 100.00%	99Rh 16.1 D < 100.00%	100Rh 20.8 H	101Rh 3.3 Y	102Rh 207 D	103Rh STABLE 100%	104Rh 42.3 S 8-: 99 55%	105Rh 35.36 H 8-: 100.00%
e. 100.00%	e. 100.00%	0.100.00%	£. 100.00%	e. 100.00%	e. 100.00%	2. 100.00%	β-: 22.00%		ε: 0.45%	p . 100.00%
94Ru 51.8 M €: 100.00%	95Ru 1.643 H €: 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D € 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H	94Tc 293 M	95Tc 20.0 H	96Tc 4.28 D	97Tc 4.21E+6 Y	98Tc 4.2E+6 Y	99Tc 2.111E+5 Y	100Tc 15.46 S	101Tc 14.22 M	102Tc 5.28 S	103Tc 54.2 S
e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% ε: 1.8E-3%	β-: 100.00%	β-: 100.00%	β-: 100.00%
92Mo STABLE 14.84%	93Мо 4.0E+3 Y	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D	100Mo 7.3E+18 Y 9.63%	101Mo 14.61 M	102Mo 11.3 M
	€: 100.00%						β-: 100.00%	2β-: 100.00%	β-: 100.00%	β-: 100.00%
91Nb 6.8E+2 Y	92Nb 3.47E+7 Y	93Nb STABLE 100%	94Nb 2.03E+4 Y	95Nb 34.991 D	96Nb 23.35 H	97Nb 72.1 M	98Nb 2.86 S	99Nb 15.0 S	100NЪ 1.5 S	101Nb 7.1 S
ε: 100.00%	€: 100.00% β− < 0.05%		β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Y	94Zr STABLE 17.38%	95Zr 64.032 D	96Zr >3.9E+20 Y 2.80%	97Zr 16.744 H	98Zr 30.7 S	99Zr 2.1 S	100Zr 7.1 S
			β-: 100.00%		β-: 100.00%	2β-	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%
89Y STABLE 100%	90Y 64.053 H	91Y 58.51 D	92Y 3.54 H	93Y 10.18 H	94Y 18.7 M	95Y 10.3 M	96Y 5.34 S	97Y 3.75 S	98¥ 0.548 S	99¥ 1.470 S
	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n: 0.058%	β-: 100.00% β-n: 0.33%	β-: 100.00% β-n: 1.90%
885r STABLE 82,58%	895r 50.57 D	90Sr 28.90 Y	91Sr 9.63 H	92Sr 2.66 H	93Sr 7.423 M	94Sr 75.3 S	95Sr 23.90 S	96Sr 1.07 S	97Sr 429 MS	98Sr 0.653 S

The Big Bang																		
Group	Group 1 2 3 4 5 6 7 8 9 10 11 12															16	17	18
Period																		
1	1 To% by mass in the Sun															y ma	ass	² He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	${{}^{12}_{{ m Mg}}}$											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	\mathbf{W}^{74}	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanth	ano	ids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Acti	noie	ls	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

The simplest H burning: the pp chain



This is the nuclear burning that powers stars like the Sun: *Energy of 4 p >*

Energy of 1 He

The Main Sequence on the Herzsprung-Russell (H-R) diagram



More H burning: the CNO cycle. The net result is the conversion of C and O into N



						Τ	⁻h€	e E	Big	Ba	ng		Η	bu				
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	$\frac{1}{H}$]																² He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	${{ m Mg}}^{12}$											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanth	ano	ids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Acti	noid	ls	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		
The nuclide chart

							e: 100.00%				
•	Numbe	er of			10N	11N 1.58 MeV	12N 11.000 MS	13N 9.965 M	14N STABLE 99.634%	15N STABLE 0.366%	7
A	proton	s Z			P: 100.00%	P: 100.00%	ε: 100.00%	e: 100.00%			β-: β-α
	· ·			8C 230 KeV	9C 126.5 MS	10C 19.290 S	11С 20.334 М	12C STABLE 98.89%	13C STABLE 1.11%	14C 5700 Y	2
L				P: 100.00% a	ε: 100.00% εp: 61.60%	ε: 100.00%	€: 100.00%			β-: 100.00%	β-:
I			6B	7B 1.4 MeV	8B 770 MS	9B 0.54 KeV	10B STABLE 19.8%	11B STABLE 80.2%	12B 20.20 MS	13B 17.33 MS	1
			2P	d P	εα: 100.00% ε: 100.00%	2a: 100.00% P: 100.00%			β-: 100.00% B3A: 1.58%	β-: 100.00%	β-: β-:
L			5Be	6Be 92 KeV	7Be 53.22 D	8Be 5.57 eV	9Be STABLE 100.%	10Be 1.51E+6 Y	11Be 13.81 S	12Be 21.49 MS	: 2.7
			Р	a: 100.00% P: 100.00%	€: 100.00%	a: 100.00%		β-: 100.00%	β-: 100.00% β-α: 3.1%	β-: 100.00% β-n≤ 1.00%	
I		3Li	4Li 6.03 MeV	5Li ≈1.5 MeV	6Li STABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS	9Li 178.3 MS	10Li	11Li 8.59 MS	<
		Р	P: 100.00%	P: 100.00% a: 100.00%			β-α: 100.00% β-: 100.00%	β-: 100.00% β-n: 50.80%	N: 100.00%	β-: 100.00% β-no: 0.027%	
I			3He STABLE 0.000137%	4He STABLE 99.999863%	5He 0.60 MeV	6He 806.7 MS	7He 150 KeV	8He 119.1 MS	9He	10He 300 KeV	
L					N: 100.00% at: 100.00%	β-: 100.00%	N	β-: 100.00% β-n: 16.00%	N: 100.00%	N: 100.00%	
L		1H STABLE 99.985%	2H STABLE 0.015%	3H 12.32 Y	4H 4.6 MeV	5H 5.7 MeV	6H 1.6 MeV	7H 29E-23 Y			
				β-: 100.00%	N: 100.00%	N: 100.00%	N: 100.00%	2N?			
			Neutron 10.23 M								
			β-: 100.00%								

Number of neutrons N

Which nuclear masses do not exist in stable form:





3. 1, 2, and 3

4. 5 and 7

He burning: The triple alpha (α = ⁴He) reaction



He burning & the "Hoyle" state





kТ

Eo



He burning: The triple alpha (α = ⁴He) reaction



						Τ	The Big Bang						H burning					
Group	1	2	3	4	5	6	7	8	9	10	11	12				•	7	18
Period													He burning					
1	$\frac{1}{\mathrm{H}}$]										L]	² He
2	3 Li	4 Be											5 B	б С	7 N	8	9 F	10 Ne
3	11 Na	${}^{12}_{\mathrm{Mg}}$											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids 57 58 59 6 La Ce Pr N				60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb				
**Actinoids 89 90 91 Ac Th Pa			92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No					

In stars < 10 the mass of the Sun...



...the core can reach 100 MK needed for He burning, after that it will become a white dwarf

In stars > 10 the mass of the Sun...



... the core can get hotter and keep burning



Once formed, the evolution of a star is governed by gravity:

continuing contraction to higher central densities and temperatures



Carbon and Oxygen Burning



on Burning		
$^{2}C \rightarrow {}^{24}Mg + \gamma$,	13.931
$\rightarrow {}^{23}\text{Mg} + n$,	-2.605
\rightarrow ²³ Na + p	,	2.238
\rightarrow ²⁰ Ne + α	,	4.616
ightarrow ¹⁶ O +2 $lpha$,	,	-0.114
	on Burning ${}^{2}C \rightarrow {}^{24}Mg + \gamma$ $\rightarrow {}^{23}Mg + n$ $\rightarrow {}^{23}Na + p$ $\rightarrow {}^{20}Ne + \alpha$ $\rightarrow {}^{16}O + 2\alpha$	on Burning ${}^{2}C \rightarrow {}^{24}Mg + \gamma ,$ $\rightarrow {}^{23}Mg + n ,$ $\rightarrow {}^{23}Na + p ,$ $\rightarrow {}^{20}Ne + \alpha ,$ $\rightarrow {}^{16}O + 2\alpha ,$

Average $Q = 13 \,\mathrm{MeV}$

Oxygen Burning

$^{16}O + ^{16}O$	\rightarrow	³² S	$+\gamma$,	16.541
	\rightarrow	³¹ P	+ p	,	7.677
	\rightarrow	³¹ S	+ n	,	1.453
	\rightarrow	²⁸ Si	+α	,	9.593
	\rightarrow	²⁴ Mg	+ 2a	έ,	-0.393

Average $Q = 16 \,\mathrm{MeV}$

Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}{
m Ne} + \gamma
ightarrow {}^{16}{
m O} + {}^{4}{
m He} \ , \quad Q = -4.73 \, {
m MeV}$$

This reaction dominates over the inverse reaction known from helium burning for $T>1.5 imes10^9$ K.

Subsequently, the ⁴He is captured on another ²⁰Ne nucleus: ²⁰Ne + ⁴He \rightarrow ²⁴Mg + γ .

The net result is $2\,{}^{20}\mathrm{Ne} + \gamma \rightarrow \,{}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + \gamma \;, \quad Q = +4.583\,\mathrm{MeV}$

Nuclear burning phases for a 20 $\rm M_{\odot}$ star

Fuel	Main Product	Secondary Product	T (10 ⁹ K)	Time (yr)	Main Reaction
н	He	¹⁴ N	0.02	10 ⁷	с [№] 4 H → ⁴ He
Не	O , C	¹⁸ O, ²² Ne s-process	0.2	10 ⁶	3 He ⁴ → ¹² C ¹² C(α,γ) ¹⁶ O
С	Ne, Mg	Na	0.8	10 ³	¹² C + ¹² C
Ne	O, Mg	AI, P	1.5	3	²⁰ Ne(γ,α) ¹⁶ O ²⁰ Ne(α,γ) ²⁴ Mg
Ο	Si, S	CI, Ar, K, Ca	2.0	0.8	¹⁶ O + ¹⁶ O
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	²⁸ Si(γ,α)

Nuclear Statistical Equilibrium

When the strong and the electromagnetic interactions come into equilibrium, the nuclear abundances depend only on the temperature T, density ρ , and neutron-richness Y_e.



Favours the production of the **nuclei with the highest binding energy per nucleon** The binding energy per nucleon is the average energy needed to "break off" one nucleon from the nucleus.



Core Collapse/Type II (H-rich) Supernovae



Thermonuclear/Type I (no H) Supernovae:

explosion of a white dwarf that has reached the Chandrasekhar mass, how?

THIS...













Beyond Fe

- Need to add energy to do fusion
- Nuclear reactions do not contribute anymore to the energy of a star
- High coulomb barrier prevents proton or alpha captures, because they are charged
- Have to add neutrons to make heavier elements!



Because of their high number of protons (>26), elements heavier than Fe have a large Coulomb barrier and can be produced only by capturing neutrons.

Slow and Rapid neutron captures



r-only s-only p-only

a 1:	26 54 s	La 127	La 128	La 129 11.6 m	La 130 8.7 m	La 131 59 m	La 132 24.3 m 4.8 h	La 133 3.91 h	La 134 6.67 m	La 135 19.4 h	La 136 9.9 m	La 137 6 · 10⁴ a	La 138 0.090	La 139 99.910
β γ 4	3+ / 256; !55	$\beta^{+}_{\gamma 56;}$ β^{+}_{25}	$\begin{array}{ccc} \beta^+ & \beta^+ \\ \gamma 284; & \gamma 284; \\ 659 & 679 \end{array}$	$ \begin{array}{c} \beta^{+} \ 2.4; \ 2.7 \\ \gamma \ 279; \ 111; \\ 254; \ 457 \\ g \end{array} $	β ⁺ γ 357; 551; 544; 908	$\stackrel{\varepsilon}{\beta^+}$ 1.4; 1.9 γ 108; 418; 365; 286; g	$\begin{array}{c} \beta^+ \ 3.2;\\ i\gamma \ 135 \ 3.7\\ \beta^+ \ \gamma \ 465;\\ \gamma \ 465; \ 567; \ 663;\\ 285 \ 1910\end{array}$	ε; β ⁺ 1.2 γ 279; 302; 290; 633; 618 α	β ⁺ 2.7 γ 605; (1555)	ε; β ⁺ γ 481; (875; 588) g	ε β ⁺ 1.9 γ 819; (761; 1323)	e noγ g	1.05 · 10 ¹¹ a ε; β ⁻ 0.3 γ 1436; 789 σ.57	σ 9.2
a 1	25 3.5 m	Ba 126 100 m	Ba 127 1.9 s 12.7 m	Ba 128 2.43 d	Ba 129 2.13 h 2.20 h	Ba 130 0.106	Ba 131 14.5 m 11.5 d	Ba 132 0.101	Ba 133 38.9 h 10.5 a 1γ 276;	Ba 134 2.417	Ba 135 28.7 h 6.592	Ba 136 7.854	Ba 137 2.55 m 11.232	Ba 138 71.698
β γ 1 5 8	3 ⁺ 3.4 / 78; 41; 35	^ε β ⁺ γ 234; 258; 241	$\begin{array}{c} \beta^{+} 2.4\\ \gamma \ 181;\\ 115;\\ 24\\ \end{array}$	ε no β+ γ 273	$\begin{array}{ccc} \varepsilon & \beta^{+} \ 1.4 \\ \gamma \ 182; & \gamma \ 214; \\ 1459; & 221; \\ 202 & 129 \end{array}$	σ 1+8	β ⁺ 79 124; e ⁻ 216	σ084+97	12 € e	<u>σ</u> 0.1 + 1.5	lγ 268 e σ 5.8	σ 0.010 + 0.44	lγ 662 σ 5	σ 0.41
s 1	24 30.8 s	Cs 125 45 m	Cs 126 1.6 m	Cs 127 6.25 h	Cs 128 3.8 m	Cs 129 32.06 h	Cs 130 3.46 m 29.21 m	Cs 131 9.69 d	Cs 132 6.47 d	Cs 133 100	Cs 134 2h 2.06 a	Cs 135 53 m 2 · 10 ⁶ a	Cs 136	Cs 137 30.17 a
2; γ 9 4	3 ⁺ 4.9 354; 15; 193	 ϵ; β⁺ 2.1 γ 526; 112; 412 g 	β ⁺ 3.8 γ 389; 491; 925	$ \begin{matrix} \varepsilon \\ \beta^+ \ 0.7; \ 1.1 \\ \gamma \ 411; \ 125; \\ 462; \ q \end{matrix} $	β ⁺ 2.9 γ 443; 527	ε β+ γ 372; 411; 549; g	$ \begin{array}{ll} & I\gamma 80; & \epsilon \\ & 51; & \beta^+ 2.0 \\ & 148 & \beta^- 0.4 \\ & \epsilon & \gamma 536., \end{array} $	ε no β ⁺ no γ g	ε; β ⁺ β ⁻ 0.8 γ 668; 465; 630 σ _{n, α} <0.15	σ 2.7 + 27.5	β 0.7 γ 605; 796 β ⁺ e ⁻ σ	β ⁻ 0.2 no γ 840 σ 8.3	β 0.3; 0.7 γ 819; 1048 Ιγ σ 1.3	$\beta^{-} 0.5; 1.2$ m; g $\sigma 0.20 + 0.07$
(e 1 2.08	23 h	Xe 124 0.0952	Xe 125 57 s 16.9 h	Xe 126 0.0890	Xe 127 70 s 36.4 d	Xe 128 1.9102	Xe 129 8.89 d 26.4006	Xe 130 4.0710	Xe 131 11.9 d 21.2324	Xe 132 26.9086	Xe 133 2.1.1 5.25 d	Xe 134 10.4357	Xe 135	Xe 136 8.8573
1.5 9; 17	8;	x 28 + 137	ε; β ⁺ γ 188; 243; 55 140 σ _{n, α} ~0. L	σ045+3.0	€ γ 203; 172; 375 173 σ _{n, α} <0.01	т 0.48 + 4.7.	γ 40; 197 e σ 22	σ́ 0.45 + 4.35	lγ 164 e σ 90	σ 0.05 + 0.40	β ⁻ 0.3 γ 81 e ⁻ e ⁻ σ 190	σ0.003 + 0.26	$\begin{array}{ccc} l_{\gamma} 527 & \beta^- 0.9 \\ \beta^- & \gamma 250; \\ \gamma (787) & 608; g \\ g & \sigma 2.65\cdot 10^6 \end{array}$	σ 0.26
12 3.6	22 m	l 123 13.2 h	l 124 4.15 d	l 125 59.41 d	l 126 13.11 d	l 127 100	l 128	l 129 1.57 · 10 ⁷ a	I 130 9.0 m 12.36 h	l 131 8.02 d	I 132 83.6 m 2.30 h	I 133 9 s 20.8 h	I 134 3.5 m 52.0 m	l 135 6.61 h
3.1 i4		ε no β ⁺ γ 159 g	ε β ⁺ 2.1 γ 603; 1691; 723	¢ γ 35; e ⁻ g σ 900	ε; β ⁻ 0.9; 1.3 β ⁺ 1.1 γ 389; 666 σ 5960	σ 6.2	ε; β ⁺ γ 443; 527 σ 22	$\beta^{-} 0.2$ $\gamma 40$ $e^{-}; g$ $\sigma 20.7 + 10.3$	β ⁻ 1.0; e ⁻ γ 536; β ⁻ 2.5 669; 739 γ 536 σ 18	$\begin{array}{c} \beta^{-} \ 0.6; \ 0.8\\ \gamma \ 364; \ 637;\\ 284; \ g\\ \sigma \sim 0.7 \end{array}$	$\begin{array}{c c} & \beta^{-} 2.1\\ \beta^{-} 1.5 & \gamma \ 668;\\ \gamma \ 668; & 773;\\ 773; \ 600; & 955;\\ 175 & 523\end{array}$	β ⁻ 1.2; 1.5 Iγ 913; γ 530; 647; 875 73 g	$\begin{array}{ccc} 1\gamma \ 272; \\ 44 & \beta^- \ 1.3; \\ \beta^- \ 2.5 & 2.4 \\ \gamma \ 847; & \gamma \ 847; \\ 884; \ 234 & 884 \end{array}$	β 1.5; 2.2 γ 1260; 1132; 1678; 1458 g; m
e 1	21 16.8 d	Te 122 2.55	Te 123 0.89	. Te 124 4.74	Te 125 57.4 d 7.07	Te 126 18.84	Te 127 10 9.35 h	Te 128 31.74	Te 129 33.6 d 69.6 m	Te 130 34.08	Te 131 30 h 25.0 m	Te 132 76.3 h	Te 133	Te 1 41.8
2 5	y 573; 508	⊄ 04+3	10 ¹³ a ε; no γ σ 370 σ α.0.0000	σ 1+6	γ (35) e	σ 0.12 + 0.8	Ιγ (88) e ⁻ β ⁻ 0.7 γ (58) γ 418	$7.2 \cdot 10^{-4} a$ $2\beta^{-}$ $\sigma = 0.03 \pm 0.2$	$ \begin{array}{ccc} I_{\gamma} \ (106) & \beta^- 1.5 \\ e^- & \gamma \ 28; \\ \beta^- 1.6 & 460; \\ \gamma \ 696 & 487 \end{array} $	$2.7 \cdot 10^{-1} \text{ a}$ $2\beta^{-1}$ > 0.01 + 0.19	2.5 γ 774; β 2.1 β52 γ 150; γ 182 452	β 0.2 γ 228; 50 g	3.3 2. γ 913; γ 3 648; g 408; Ιγ 334 1333; g	р 0.6; 0.7.4 у 767; 210; 78; 79; 566 9
6b 1	20 15.9 m	Sb 121 57.21	Cb 122 4.2 m. 2.70 d	Sb 123 42.79	Sb 124	Sb 125 2.77 a	Sb 126	Sb 127 3.85 d	Sb 128	Sb 129 17.7 m 4.40 h	Sb 130	Sb 181 23 m	Sb 132	Sb 133 2.5 h
- 1; ε β0 η	з ⁺ 1.7 у 1171	σ 0.4 + 5.8	$\begin{array}{c} 1.4;\\ 2.0\\ \epsilon; \beta^+\\ 76\\ \gamma 564;\\ e^- \\ 693\end{array}$	σ 0.02 + 0.04 - 4.0	$\begin{array}{c} (25) \\ e^{-} \\ \gamma 603; \\ 646 \\ \sigma 17 \end{array} \begin{array}{c} \beta^{-} 0.0; \\ \gamma 603; \\ 1691 \\ \sigma 17 \end{array}$	$\begin{array}{c} \beta^{-} \ 0.3; \ 0.6 \\ \gamma \ 428; \ 601; \\ 636; \ 463 \\ g; \ m \end{array}$	γ 415; 1.9 γ 415; 1.9 666 γ 666; Ιγ (23) Ιγ (18) 695; e ⁻ e ⁻ 415	β 0.9; 1.5 γ 686; 473; 784 g; m	γ 743; γ 743; γ 743; γ 743; 754; 754; 314 314; Ιγ 527	γ 760; 2.2 658 γ 813; Iy 1129; 915 723; m; g	$\begin{array}{c c} \gamma & 840; \\ 793; \\ 331; \\ 182 \\ \end{array} \begin{array}{c} \gamma & 840; \\ 40; \\ 182 \\ 182 \\ \end{array}$	β 1.3; 3.0 γ 943; 933; 642 m	$\begin{array}{c} \beta^{-} 3.9 \\ 697; \\ 151; \\ 104 \end{array} \beta^{-} 3.9 \\ \gamma \ 974; \\ 597; \\ \ldots \end{array}$	β 1.2; 2.4 γ 1096; 818; 2755; 837 g; m
Sn 1	19 8.59	Sn 120 32.58	∼50 a 27.0 h	Sn 122 4.63	Sn 123 40.1 m 129.2 d	Sn 124 5.79	Sn 125 9.5 m 9.64 d	Sn 126 2.345 · 10⁵ a	Sn 127 4.1 m 2.1 h	Sn 12 6.5 s 59.1	Sn 129 6.9 m 2.2 m	S. 130 1.7 m 1.7 m	Sn 131 50 s 39 s	Sn 132 39.7 s
	r 2	σ 0.001 + 0.13	Ιγ (6) β¯ 0.35 γ.37 β ^{−−} 0.38 e [−] no γ	0 15 ± 0 001	β 1.3 γ 160 γ (1089)	σ0.13 + 0.004	β ⁻ 2.4 γ 1067; 1089; β ⁻ 2.0 823; γ 332 916	β 0.3 γ 88; 64; 7. m	β 3.2. γ 1114; β 2.7 1096; γ 491 823	β 0.7 γ 482; 75; 557; 681 m	γ 1.28. 1128. 7645; 761 m	p ~4 β γ 145; 1.5 899; γ 192; 84; 780; 311; m 70; g	β 3.4 γ 1226; 450; 95; 95; β 3.9 γ 798	β 8 γ 341,936; 899; 247; 95 g
n 1 ¹ 4.4 π β ⁻ 1.3	18 n 5 s 3; 8= 4 2	In 119 18 m 2.3 m β ⁻ 2.7 γ (1055)	In 120 47.3 s 46.2 s 3.1 s β ⁻ 2.1 β ⁻ 2.2; 42	In 121 3.8 m 23.1 s β ⁻ 2.5 9.925	In 122 10.8 s 10.3 s β ^{-3.0} β ^{-4.4} ρ= 5.5	In 123 47.8 s 5.98 s β ⁻ 4.5 β ⁻ 3.3; ×126: 34	In 124 3.7 s 3.17 β ^{-3.7;} β ^{-4.1;} 5162	In 125 2.2 s 2.3 s β ⁻ 4.1; 4.3;	1.64 1.60 s	In 1.27 1.04s 3.67s 98 β ⁻ 4.8; 6 ⁻ 7.0., β ⁻ 5.0	In 128 0.72 s 0.84 s β ^{-5.3;} β ^{-5.5;} 58 7.6	In 129 57s 1.23s 0.61s β 7.69 = 8.170	Π1130 0.53s 0.53s 0.33s β ⁻ β ⁻ ν2259 ν1221; ν	In 131 0.32s 0.35s 0.28s β ⁻ 6.6; β ⁻ 9.2 β ⁻ 6.8 8.8

Which of these statements is wrong?

95Rh 5.02 M	96Rh 9.90 M	97Rh 30.7 M	98Rh 8.72 M	99Rh 16.1 D	100Rh 20.8 H	101Rh 3.3 Y	102Rh 207 D	103Rh STABLE	104Rh 42.3 S	105Rh 35.36 H
e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	€: 78.00% β∹: 22.00%	100%	β∹: 99.55% ε: 0.45%	β-: 100.00%
94Ru 51.8 M € 100.00%	95Ru 1.643 H € 100.00%	96Ru STABLE 5.54%	97Ru 2.791 D € 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%
93Tc 2.75 H	94Tc 293 M	95Tc 20.0 H	96Tc 4.28 D	97Tc 4.21E+6 Y	98Tc 4.2E+6 Y	99Tc 2.111E+5 Y	100Tc 15.46 S	101Tc 14.22 M	102Tc 5.28 S	103Tc 54.2 S
e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% ε: 1.8E-3%	β-: 100.00%	β-: 100.00%	β-: 100.00%
92Mo STABLE 14.84%	93Мо 4.0E+3 Ү €:100.00%	94Mo STABLE 9.25%	95Mo STABLE 15.92%	96Mo STABLE 16.68%	97Mo STABLE 9.55%	98Mo STABLE 24.13%	99Mo 2.7489 D β-: 100.00%	100Mo 7.3E+18 Υ 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%
91№ 6.8Е+2 ¥	92Nb 3.47E+7 Y	93Nb STABLE 100%	94Nb 2.03E+4 Y	95Nb 34.991 D	96Nb 23.35 H	97Nb 72.1 M	98Nb 2.86 S	99Nb 15.0 S	100Nb 1.5 S	101Nb 7.1 \$
e: 100.00%	ε: 100.00% β− < 0.05%		β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%
90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.53E+6 Υ β-: 100.00%	94Zr STABLE 17.38%	952r 64.032 D β-: 100.00%	96Zr >3.9E+20 ¥ 2.80% 2β-	972r 16.744 H β-: 100.00%	98Zr 30.7 S β-: 100.00%	99Zr 2.1 S β-: 100.00%	100Zr 7.1 S β-: 100.00%
89Y STABLE 100%	90Y 64.053 H	91¥ 58.51 D	92Y 3.54 H	93Y 10.18 H	94Y 18.7 M	95¥ 10.3 M	96Y 5.34 S	97Y 3.75 S	98¥ 0.548 S	99¥ 1.470 S
	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n: 0.058%	β-: 100.00% β-n: 0.33%	β-: 100.00% β-n: 1.90%
88Sr STABLE 82.58%	895r 50.57 D	90Sr 28.90 Y	91Sr 9.63 H	92Sr 2.66 H	93Sr 7.423 M	94Sr 75.3 S	95Sr 23.90 S	96Sr 1.07 S	97Sr 429 MS	985r 0.653 S
	p 100.00%	p 100.00%	p 100.00%	p 100.00%	p 100.00%	p 100.00%	p 100.00%	p 100.00%	p 100.00% β-n≤ 0.05%	р 100.00% 8-n: 0.25%

Hint: Track the *s*- and *r*-process path on the nuclide chart.

- 1. Mo has one p-only isotope
- 2. Zr does not have any s-only isotopes
- 3. Ru has one r-only isotope
- 4. Zr and Mo have one r-only isotope each

Where does the s process happen?



Merrill 1952, Burbidge et al. 1957 Which processes produce the long-lived $(T_{1/2} > 0.1 \text{ Myr})$ isotopes of Tc?

1. the *p* and the *s* processes

2. the *p* process

3. the *r* and the *p* process

4. the r, s, and p processes



If the *s* process happens in the "peculiar stars", which isotopes of Tc are we are seeing in these stars?





3.99 and 100





Stars < 10 the mass of the Sun...



...go through the asymptotic giant branch (AGB) before becoming white dwarfs.



Artist impression.

Wavelength (µm)

Courtesy of Pedro Garcia-Lario, ESA and Anibal García-Hernandez, IAC



Extended convective envelope

Compact core









time

The neutron sources



time
The neutron sources



time

The neutron sources



time

Neutron density (cm⁻³): defines the details of the s-process path ²²Ne >> ¹³C

²²Ne

10¹³ cm⁻³

Neutron exposure τ (mbarn⁻¹): defines the details of the overall distribution ¹³C >> ²²Ne



The **neutron density** is the key quantity the defines the final abundances around *branching points*

Second Second														
a 1	26 54 s	La 127	La 128	La 129 11.6 m	La 130 8.7 m	La 131 59 m	La 132 24.3 m 4.8 h	La 133 3.91 h	La 134 6.67 m	La 135 19.4 h	La 136 9.9 m	La 137 6 · 10⁴ a	La 138 0.090	La 139 99.910
р 2	β ⁺ γ 256; 455	$\beta^{+}_{\gamma 56;}$ β^{+}_{25}	$\begin{array}{ccc} \beta^+ & \beta^+ \\ \gamma 284; & \gamma 284; \\ 659 & 679 \end{array}$	$ \begin{array}{c} \beta^{+} \ 2.4; \ 2.7 \\ \gamma \ 279; \ 111; \\ 254; \ 457 \\ g \end{array} $	β ⁺ γ 357; 551; 544; 908	$\stackrel{\varepsilon}{\beta^+} \stackrel{1.4; 1.9}{\gamma 108; 418;} \\365; 286; g$	$\begin{matrix} \beta^+ 3.2;\\ 3.7\\ \beta^+ & \gamma 465;\\ \gamma 465; & 567; 663;\\ 285 & 1910 \end{matrix}$	$\begin{array}{l} \varepsilon; \ \beta^{+} \ 1.2 \\ \gamma \ 279; \ 302; \\ 290; \ 633; \ 618 \\ g \end{array}$	β ⁺ 2.7 γ 605; (1555)	ε; β ⁺ γ 481; (875; 588) g	ε β ⁺ 1.9 γ 819; (761; 1323)	ε no γ g	1.05 · 10 ¹¹ a ε; β ⁻ 0.3 γ 1436; 789 σ 57	σ 9.2
a 1	25 3.5 m	Ba 126 100 m	Ba 127 1.9 s 12.7 m	Ba 128 2.43 d	Ba 129 2.13 h 2.20 h	Ba 130 0.106	Ba 131 14.5 m 11.5 d	Ba 132 0.101	Ba 133 38.9 h 10.5 a ¹ γ 276;	Ba 134 2.417	Ba 135 28.7 h 6.592	Ba 136 7.854	Ba 137 2.55 m 11.232	Ba 138 71.698
β γ 1 5 8	β ⁺ 3.4 γ 78; 141; 85	β ⁺ γ 234; 258; 241	β ⁺ 2.4 γ 181; Ιγ 56; 115; 24 66	ε no β ⁺ γ 273	$ \begin{array}{c} \epsilon & \beta^+ \ 1.4 \\ \gamma \ 182; & \gamma \ 214; \\ 1459; & 221; \\ 202 & 129 \end{array} $	σ 1 + 8	β ⁺ lγ 108; γ 496; 79 124; e [−] 216	σ 0.84 + 9.7	12 ε e^- γ 356; ε 81; 303 γ (633) σ 4	σ́ 0.1 + 1.5	lγ 268 e σ 5.	σ 0.010 + 0.44	lγ 662 σ 5	σ 0.41
s 1	24 30.8 s	Cs 125 45 m	Cs 126 1.6 m	Cs 127 6.25 h	Cs 128 3.8 m	Cs 129 32.06 h	Cs 130 3.46 m 29.21 m	Cs 131 9.69 d	Cs 132 6.47 d	Cs 133 100	Cs 134 2. h 2.06 a	Cs 135 5 1 2 · 10 ⁶ a	Cs 136	Cs 137 30.17 a
2; β	β ⁺ 4.9 γ 354; 915; 493	$\epsilon; \beta^+ 2.1$ $\gamma 526; 112;$ 412 g	β ⁺ 3.8 γ 389; 491; 925	$ \begin{array}{c} \varepsilon \\ \beta^+ \ 0.7; \ 1.1 \\ \gamma \ 411; \ 125; \\ 462; \ g \end{array} $	β ⁺ 2.9 γ 443; 527	ε β+ γ 372; 411; 549; g	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	ε no β ⁺ no γ g	ε; β ⁺ β ⁻ 0.8 γ 668; 465; 630 σ _{n, α} <0.15	σ 2.7 + 27.3	β 0.7 γ 605; 796 ε σ 140	8 ⁻ 0.2 Ιγ 781; g 840 σ 8.3	β 0.3; 0.7 γ 819; 1048 Ιγ σ 1.3	β 0.5; 1.2 m; g σ 0.20 + 0.07
(e 1 2.08	23 3 h	Xe 124 0.0952	Xe 125 57 s 16.9 h	Xe 126 0.0890	Xe 127 70 s 36.4 d	Xe 128 1.9102	Xe 129 8.89 d 26.4006	Xe 130 4.0710	Xe 131 11.9 d 21.2324	Xe 132 26.9086	Xe 133 2.1.1 5.25 d	Xe 134 10.4357	Xe 135	Xe 136 8.8573
1.5 9; 17	78;	σ 28 + 137	 ϵ; β⁺ γ 188; 243; 155 140 σ_{n, α} ~0.03 	3 σ 0.45 + 3.0	ε γ 203; 172; 375 173 σ _{n, α} <0.01	σ 0.48 + 4.7.	lγ 40; 197 e σ 22	σ 0.45 + 4.35	lγ 164 e σ 90	σ 0.05 + 0.40	β 0.3 γ81 e ⁻ e ⁻ σ190	σ 0.003 + 0.26	$\begin{array}{ccc} I_{\gamma} 527 & \beta^{-} 0.9 \\ \beta^{-} & \gamma 250; \\ \gamma (787) & 608; g \\ g & \sigma 2.65 \cdot 10^{6} \end{array}$	σ 0.26
l 12 3.6	22 m	l 123 13.2 h	l 124 4.15 d	l 125 59.41 d	l 126 13.11 d	l 127 100	I 128	l 129 1.57 · 10 ⁷ a	I 130 9.0 m 12.36 h	l 131 8.02 d	I 132 83.6 m 2.30 h	I 133 9 s 20.8 h	I 134 3.5 m 52.0 m	l 135 6.61 h
3.1 54		ε no β ⁺ γ 159 g	ε β ⁺ 2.1 γ 603; 1691; 723	¢ γ 35; e ⁻ g σ 900	 ε; β⁻ 0.9; 1.3 β⁺ 1.1 γ 389; 666 σ 5960 	σ 6.2	ε; β ⁺ γ 443; 527 σ 22	β ⁻ 0.2 γ 40 e ⁻ ; g σ 20.7 + 10.3	$ \begin{array}{c} \beta^- 1.0;\\ \mathbf{I}\gamma~(48) & 1.8\\ \mathbf{e}^- & \gamma~536;\\ \beta^- 2.5 & 669;~739\\ \gamma~536 & \sigma~18 \end{array} $	$\begin{array}{c} \beta^{-} \ 0.6; \ 0.8\\ \gamma \ 364; \ 637;\\ 284; \ g\\ \sigma \ \sim 0.7 \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	β 1.2; 1.5 ly 913; y 530; 647; 875 73 g		β 1.5; 2.2 γ 1260; 1132; 1678; 1458 g; m
	21 16.8 d	Te 122 2.55	Te 123 0.89	Te 124 4.74	Te 125 57.4 d 7.07	Te 126 18.84	Te 127 10.11 9.35 h	Te 128 31.74	Te 129 33.6 d 69.6 m	Te 130 34.08	Te 131 30 h 25.0 m	Te 132 76.3 h	Te 133 55.4 m 12.5 m 6 0.7: 6 2.2:	Te 134 41.8 m
)2 F	ε γ 573; 508	σ 0.4 + 3	10 ¹³ a ε; no γ σ 370 ε σ, α 0.00005	5 σ1+6	lγ (35) e σ 1.1	σ 0.12 + 0.8	e β 0.7 γ (58) β 0.7 γ 418	$7.2 \cdot 10^{-1} \text{ a}$ $2\beta^{-}$ $\sigma 0.03 + 0.2$	$\begin{array}{ccc} I_{\gamma} \left(106 \right) & \beta^{-} 1.5 \\ e^{-} & \gamma 28; \\ \beta^{-} 1.6 & 460; \\ \gamma 696 & 487 \end{array}$	$2\beta^{-}$ $\sigma 0.01 + 0.19$	2.5 γ 774; β 2.1 852 γ 150; Ιγ 182 452	β 0.2 γ 228; 50 g	3.3 2.7 γ 913; γ 312; 648; g 408; Ιγ 334 1333; g	β 0.8, 0.7 γ 767; 210; 278; 79; 566 g
3b 1 8 d	20 15.9 m	Sb 121 57.21	Cb 122 4.2 m. 2.70 d	Sb 123 42.79	Sb 124 20 m 1.6 m 60.3 d	Sb 125 2.77 a	Sb 126	Sb 127 3.85 d	Sb 128	Sb 129 17.7 m 4.40 h	Sb 130 39.5 m 6.3 m	Sb 131 23 m	Sb 132 4.1 m 2.8 m	Sb 133 2.5 m
'1; € ; [ε β ⁺ 1.7 γ 1171	σ 0.4 + 5.8	$\begin{array}{ccc} & 1.4, \\ 2.0 \\ \epsilon; \beta^+ \\ 76 \\ \gamma & 564; \\ e^- & 693 \end{array}$	σ 0.02 + 0.04 + 4.0	γ(11) β 0.6, e ⁻ 2.3 β ⁻ 1.2 γ603; lγ(25) γ603; 1691 e ⁻ 646 σ 17	β ⁻ 0.3; 0.6 γ 428; 601; 636; 463 g; m	$ \begin{array}{c} \rho & 1.5 \\ \gamma & 415; \\ 666 \\ \gamma & 666; \\ \rho & 1\gamma & (18) \\ e^- & e^- & 415 \end{array} $	β 0.9; 1.5 γ 686; 473; 784 g; m	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	β β 0.0, γ 760; 2.2 658 γ 813; Iy 1129; 915 723; m; g g; m	γ 840; 3.2 793; γ 840; 331; 793; 182 182	β 1.3; 3.0 γ 943; 933; 642 g; m	$\begin{array}{cccc} \gamma & 974; & \beta^{-} 3.9 \\ 697; & \gamma & 974; \\ 151; & 697; \\ 104 & 989 \end{array}$	β = 1.2; 2.4 γ 1096; 818; 2755; 837 g; m
Sn 1	19 8.59	Sn 120 32.58	121 ~50 a 27.0 h	Sn 122 4.63	Sn 123 40.1 m 129.2 d	Sn 124 5.79	Sn 125 9.5 m 9.64 d	Sn 126 2.345 · 10⁵ a	Sn 127 4.1 m 2.1 h	Sn 128 6.5 s 59.1 m	Sn 129 6.9 m 2.2 m	Sn 130	Sn 131 50 s 39 s	Sn 132 39.7 s
	σ2	σ 0.001 + 0.13	lγ(6) β [−] 0.35 γ.37 β [−] 0.38 e [−] noγ	σ 0.15 + 0.001	β 1.3 γ 160 γ (1089)	σ 0.13 + 0.004	β ⁻ 2.4 γ 1067; 1089; β ⁻ 2.0 γ 332 916	$\beta^{-} 0.3 \\ \gamma 88; 64; 87 m$	$\begin{array}{c} \beta^{-} 3.2\\ \gamma 1114;\\ \beta^{-} 2.7 \\ \gamma 491 \\ 823 \end{array}$	p 0.7 γ 482; 75; 557; 1γ 832; 681 1169 m	$\begin{array}{cccc} \rho & 2.3\\ \gamma & 1161; & \beta^{-} & 3.3\\ 1128 & \gamma & 645;\\ 761 & 81\\ m & g \end{array}$	γ 145; 1.5 899; γ 192; 84; 780; 311; m 70; g	γ 1226; 450; 305; β 3.9 1229 γ 798	β 1.8 γ 341; 86; 899; 247; 993 g
n 1 4.4 r β ⁻ 1.3	18 m 5 s 3;	In 119 18 m 2.3 m β ⁻ 2.7	In 120 47.3 s 46.2 s 3.1 s β ^{-2.1} β ^{-2.2} ;	In 121 3.8 m 23.1 s β ⁻ 2.5	In 122 10.8 s 10.3 s β ^{-3.0} β ^{-4.4} 1.5 s	In 123 47.8 s 5.98 s β ^{-4.5} β ^{-3.3;}	In 124 3.7 s 3.17 s β ^{-3.7;} β ^{-4.1;}	In 125 12.2 s 2.3 s β ^{-4.1;}	In 126 1.64 s 1.60 s	In 127 1.04s 3.67s 1.09s β ^{-4.8;} π-70 (1.09s)	In 128 0.72 s 0.84 s β ⁻ 5.3; β ⁻ 5.5;	In 129 0.67s 1.23s 0.61s β ^{-5.4;} 0.581 β ^{-5.7;}	In 130 0.53s 0.53s 0.33s β ⁻ 12250 11221 β ⁻	In 131 0.32s 0.35s 0.28s β ⁻ 6.6; β ⁻ 9.2 β ⁻ 6.8

Branching points can appear depending on the neutron density! If the neutron density is around 10¹¹ cm⁻³ we will have a branching when half lives are greater than a few days, are there any branching points here?

95Rh 5.02 M	96Rh 9.90 M	97Rh 30.7 M	98Rh 8.72 M	99Rh 16.1 D	100Rh 20.8 H	101Rh 3.3 Y	102Rh 207 D	103Rh STABLE	104Rh - 3 S	105Rh 35.36 H
ε: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	ε: 78.00% β−: 22.00%	1 20	β-: 99.55% ε: 0.45%	β-: 100.00%
94Ru 51.8 M	95Ru 1.643 H	96Ru STABLE	97Ru 2.791 D	98Ru STABLE	99Ru SZADIE	100Ru	101Ru	102Ru	osRu 50 6 D	104Ru STABLE
€: 100.00%	€: 100.00%	5.54%	€: 100.00%	1.87%	12. %	12.60%	17.06%	31.55%	β-: 100.00%	18.62%
93Tc 2.75 H	94Tc 293 M	95Tc 20.0 H	96Tc 4.28 D	97Tc 4.21E+6 Y	98Tc 4.2E+6 Y	99Tc 2.11, F+5 Y	100Tc 15.46 S	101Tc 14.22 M	102Tc 5.28 S	103Tc 54.2 S
€: 100.00%	e: 100.00%	€: 100.00%	e: 100.00%	e: 100.00%	β-: 100.00%	β-: 100.0c *	β-: 100.00% ε: 1.8E-3%	β-: 100.00%	β-: 100.00%	β-: 100.00%
92Mo STABLE	93Мо 4.0E+3 Y	94Mo STABLE	95Mo STABLE	96Mo STABLE	97Mo STABLE	98Mo STABLE	9Mo 2.7. 79 D	100Mo 7.3E+18 Y	101Mo 14.61 M	102Mo 11.3 M
14.84%	e: 100.00%	9.25%	15	10.00%	9.33%	24.13%	β-: 100.00%	9.63% 2β-: 100.00%	β-: 100.00%	β-: 100.00%
91Nb 6.8E+2 Y	92Nb 3.47E+7 Y	93Nb STABLE	94Nb 2.03E+4 Y	95Nb 3- 791 D	96Nb 23.35 H	97Nb 72.1 M	98Nb 2.86 S	99Nb 15.0 S	100Nb 1.5 S	101Nb 7.1 S
e: 100.00%	€: 100.00% β− < 0.05%	100%	β-: 100.00%	β-: 100.c %	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%
90Zr STABLE 51-45%	91Zr STABLE	92Zr STABLE	93Zr 1.53E+6 Y	94Zr STABLE	95Zr 64, 32 D	96Zr >3.9E+20 Y 2 80%	97Zr 16.744 H	98Zr 30.7 S	99Zr 2.1 S	100Zr 7.1 S
			β-: 100.00%		β-: 100.0 <mark>0</mark> %	2β-	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%
89Y Stable	90Ү 64. 53 Н	91Y 58.51 D	92Y 3.54 H	93Y 10.18 H	94Y 18.7 M	95Y 10.3 M	96Y 5.34 S	97¥ 3.75 S	98¥ 0.548 S	99¥ 1.470 S
7 70	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n: 0.058%	β-: 100.00% β-n: 0.33%	β-: 100.00% β-n: 1.90%
88Sr STABLE	79Sr 50. 7 D	90Sr 28.90 Y	91Sr 9.63 H	92Sr 2.66 H	93Sr 7.423 M	94Sr 75.3 S	95Sr 23.90 S	96Sr 1.07 S	97Sr 429 MS	98Sr 0.653 S
02.30%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n≤ 0.05%	β-: 100.00% β-n: 0.25%

Branching points can appear depending on the neutron density! If the neutron density is around 10¹¹ cm⁻³ we will have a branching when half lives are greater than a few days, are there any branching points here?

95Rh	96Rh	97Rh	98Rh	99Rh	100Rh	101Rh	102Rh	103Rh	104Rh	105Rh	
5.02 M	9.90 M	30.7 M	8.72 M	16.1 D	20.8 H	3.3 Y	207 D	STABLE	3 5	35.36 H	
e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	.ε: 78.00% β−: 22.00%		β−: 99.55% ε: 0.45%	β-: 100.00%	
94Ru 51.8 M	95Ru 1.643 H	96Ru STABLE	97Ru 2.791 D	98Ru STABLE	99Ru STARLE	100Ru	101Ru	102Ru	93Ru 6 D	104Ru STABLE	
e: 100.00%	e: 100.00%	5.54%	e: 100.00%	1.87%	12. %	12.60%	17.06%	31.55%	β-: 100.00%	18.62%	Caroful
93Tc 2.75 H	94Tc 293 M	95Tc 20.0 H	96Tc 4.28 D	97Tc 4.21E+6 Y	98Tc 4.2E+6 Y	99Tc 2.11 F+5 Y	100Tc 15.46 S	101Tc 14.22 M	102Tc 5.28 S	103Tc 54.2 S	Caleiui
e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	β-: 100.00%	β-: 100.04	β−: 100.00% ε: 1.8E-3%	β-: 100.00%	β-: 100.00%	β-: 100.00%	about
92Mo STABLE	93Mo 4.0E+3 Y	94Mo STABLE	95Mo STABLE	96Mo STABLE	97Mo STABLE	98Mo STABLE	9Mo 2.7, 79 D	100Mo 7.3E+18 Y	101Mo 14.61 M	102Mo 11.3 M	102 -
14.84%	ε: 100.00%	9.25%	15	10.0	8.00%	24.13%	β-: 100.00%	9.63% 2β-: 100.00%	β-: 100.00%	β-: 100.00%	¹⁰³ Ku!
91Nb 6.8E+2 Y	92Nb 3.47E+7 Y	93Nb STABLE	94Nb 2.03E+4 Y	95Nb 3-, 991 D	бNЪ 23. 5 Н	97Nb 72.1 M	98Nb 2.86 S	99Nb 15.0 S	100Nb 1.5 S	101Nb 7.1 S	
e: 100.00%	ε: 100.00% β− < 0.05%	100%	β-: 100.00%	β-: 100.u %	β-: 100.00.	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	
90Zr STABLE	91Zr STABLE	92Zr STABLE	93Zr 1.53E+6 Y	94Zr STABLE	95Zr 64, 32 D	>3.9E, 70 Y	97Zr 16.744 H	98Zr 30.7 S	99Zr 2.1 S	100Zr 7.1 S	
			β-: 100.00%		β-: 100.00%	2β-	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	
89Y STABLE	90Y 64, 53 H	91Y 58.51 D	92Y 3.54 H	93Y 10.18 H	94Y 18.7 M	95Y 10.3 M	96Y 5.34 S	97¥ 3.75 S	98¥ 0.548 S	99Y 1.470 S	
1 V.2	β-: 100.06.	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n: 0.058%	β-: 100.00% β-n: 0.33%	β-: 100.00% β-n: 1.90%	
88Sr STABLE	79Sr 50, 7 D	0Sr 28.5 Y	91Sr 9.63 H	92Sr 2.66 H	93Sr 7.423 M	94Sr 75.3 S	95Sr 23.90 S	96Sr 1.07 S	97Sr 429 MS	98Sr 0.653 S	
02.30%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n≤ 0.05%	β-: 100.00% β-n: 0.25%	

 95 Zr is a branching point with half-life = 64 days that produces ⁹⁶Zr. What is the **branching factor** when the neutron density $N_n = 10^{10} \text{ cm}^{-3}$? (use σ_{95} = 60 mbarn, v = 2 x 10⁸ cm/s, and λ_{β} =0.693 /T_{1/2} s) 1. 1. $f = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$ 2. 0.8 3. 0.5 4. 0 $\lambda_n = N_n <\! \sigma(v)v\! >$ $\lambda_{\beta} = \ln 2/T_{1/2}$, where $T_{1/2}$ is the half-life in seconds.

The **neutron exposure** is the key quantity the defines the relative abundances of the peaks of the overall distribution: **Which elements beyond Fe have isotopes with magic number of neutrons?**



The Solar System abundances



The s-process peaks correspond to stable nuclei with neutron magic numbers N = 50, 82,126 because the neutron capture path goes rights through them.

The Solar System abundances



During the *r*-process **unstable magic nuclei** act as "waiting points"





Astrophysical sites

need a neutron-rich explosive environment

Neutron-rich jets in magnetohydrodynamical supernovae: rapid rotation and strong magnetic fields, matter collimates







August 2017: first direct evidence for the neutron star merger site





The evolution of Eu in the Galaxy

Free parameters:

- the probability of the events;
- the coalescent time for neutron star mergers.

Neutron star mergers + Jet supernovae



S	low	s pr	roce	ess	???					Rapid r process					
Ν	l _n <	101	³ cm	⁻³						$N_n > 10^{20} cm^{-3}$					
Δ 126 0 s 54 s β ⁺ γ 256; 455	La 12/ 5.1 m 3.8 m β ⁺ ^{β⁺} _{γ 56;} 25	La 128 <1.4 m 5.18 m ^{β+} β ⁺ γ 284; γ 284; 659 679	La 129 11.6 m β ⁺ 2.4; 2.7 γ 279; 111; 254; 457 9	La 130 8.7 m ^{β+} γ 357; 551; 544; 908	La 131 59 m ${}^{\epsilon}_{\beta^{+}1.4; 1.9}_{\gamma 108; 418; 365; 286; g}$	$\begin{array}{c c} La 132 \\ \hline 24.3 m & 4.8 h \\ \beta^+ 3.2; \\ \hline 1\gamma 135 & 3.7 \\ \beta^+ & \gamma 465; \\ \gamma 465; & 567; 663; \\ 285 & 1910 \end{array}$	La 133 3.91 h $\epsilon; \beta^+ 1.2$ $\gamma 279; 302;$ 290; 633; 618 g	La 134 6.67 m ^{β⁺ 2.7} γ 605; (1555)	La 135 19.4 h ε; β ⁺ γ 481; (875; 588) 9	La 130 9.9 m ^ε β ⁺ 1.9 γ 819; (761; 1323)	La 137 6 · 10 ⁴ a ^ε ^{no} γ g	La 138 0.090 1.05 · 10 ¹¹ a ε; β ^{-0.3} γ 1436; 789 σ 57	La 139 99.910 _{09.2}		
$\begin{array}{c c} 3a & 125 \\ m & 3.5 m \\ & \beta^{+} 3.4 \\ \gamma & 78; \\ 141; \end{array}$	Ba 126 100 m ^ϵ _β + γ 234; 258;	Ba 127 1.9 s 12.7 m β ⁺ 2.4 γ 181; 115;	Ba 128 2.43 d	Ba 129 2.13 h 2.20 h ^ϵ β ⁺ 1.4 γ 182: γ 214; 1459; 221;	Ba 130 0.106	Ba 131 14.5 m 11.5 d ⁶ / _γ + γ 496; 79 124; 124;	Ba 132 0.101	Ba 133 38.9 h 10.5 a ¹ / ₂ 276; ¹² ¢ e ⁻ y 356; 81; 303	Ba 134 2.417	Ba 135 28.7 h 6.592	Ba 136 7.854	Ba 137 2.55 m 11.232	Ba 138 71.698		
5 85 Cs 124 3s 30.8 s β ⁺ 4.9 γ 354; 915; 493	$\begin{array}{c} 241\\ \hline Cs \ 125\\ 45 \ m\\ \epsilon; \ \beta^{+} \ 2.1\\ \gamma \ 526; \ 112;\\ 412\\ g\end{array}$	24 66 Cs 126 1.6 m β ⁺ 3.8 γ 389; 491; 925	$\begin{array}{c} \gamma 2/3 \\ \hline Cs 127 \\ 6.25 h \\ \epsilon \\ \beta^{+} 0.7; 1.1 \\ \gamma 411; 125; \\ 462; g \end{array}$	202 129 Cs 128 3.8 m β ⁺ 2.9 γ 443; 527	Cs 129 32.06 h ^ϵ _β + _γ 372; 411; 549; g	$\begin{array}{c c} e & 216\\ \hline CS & 130\\ 3.46 m & 29.21 m\\ {}^{l\gamma 80;} & \epsilon\\ 51; & \beta^+ 2.0\\ 148 & \beta^- 0.4\\ \epsilon & \gamma 536. \end{array}$	Cs 131 9.69 d ^ε no β ⁺ no γ g	$\begin{array}{c} \begin{array}{c} & \sigma_{4} \\ \hline \\ Cs \ 132 \\ 6.47 \ d \\ \hline \\ \phi_{5} \phi_{1}^{+} \\ \phi_{668} & 465; 630 \\ \sigma_{n,\alpha} < 0.15 \end{array}$	Cs 133 100 σ2.7 + 27.5	e σ5.8 CS 134 2. h 2.06 a 9 - 0.7 φ 605; 796 e ⁻ σ140	Cs 135 53 m 2 · 10 ⁶ a β ⁵ 0.2 00 γ g 6.3	γ στ2 στ5 Cs 136 19 s 13.16 d β ⁻ 0.3; 0.7 γ 819; 1048 Ιγ 1.3	Cs 137 30.17 a β ⁻ 0.5; 1.2 m; g σ 0.20 + 0.07		
(e 123 2.08 h ^{1.5} ^{49; 178;}	Xe 124 0.0952 σ 28 + 137	Xe 125 57 s 16.9 h ε; β ⁺ γ 188; 243; 140 55 σn. α ~0.03	Xe 126 0.0890 σ 0.45 + 3.0	Xe 127 70 s 36.4 d ^ε γ 203; 172; 375 σ _{n, α} <0.01	Xe 128 1.9102 σ 0.48 + 4.7.	Xe 129 8.89 d 26.4006	Хе 130 4.0710 ^{о 0.45 + 4.35}	Хе 131 11.9 d 21.2324 ^{ју 164} г ^{. 90}	Xe 132 26.9086 σ 0.05 + 0.40	Xe 133 2.1 5.25 d β ⁻ 0.3 γ81 e ⁻ σ190	Xe 134 10.4357 σ 0.003 + 0.26	Xe 135 15.3 m 9.10 h ^{Ιγ} 527 ^{β⁻} ^{γ(787)} ^g ^{θ0.9} ^{γ250;} ^{γ250;} ^{γ250;} ^{γ250;} ^{γ250;}	Xe 136 8.8573 σ 0.26		
I 122 3.6 m	I 123 13.2 h ^ϵ no β ⁺ γ 159 g	$\begin{matrix} \textbf{I} \ \textbf{124} \\ \textbf{4.15} \ \textbf{d} \\ \overset{\varepsilon}{}_{\beta^{+} 2.1} \\ _{\gamma \ 603; \ 1691;} \\ _{723} \end{matrix}$	l 125 59.41 d [€] γ 35; e [−] ⁹ σ 900	$\begin{array}{c} I \ 126 \\ 13.11 \ d \\ \varepsilon; \beta^{-} \ 0.9; \ 1.3 \\ \beta^{+} \ 1.1 \\ \gamma \ 389; \ 666 \\ \sigma \ 5960 \end{array}$	I 127 100 σ6.2	1128 5.0 m ε; β ⁺ γ443; 527 σ 22	I 129 1.57 · 10 ⁷ a ^{β⁻ 0.2} γ 40 e ⁻ ; g σ 20.7 + 10.3	I 130 9.0 m 12.36 h β ⁻ 1.0; 1.8 e ⁻ γ 536; γ 536 σ 18	$\begin{array}{c} 1 \ 131 \\ 8.02 \ d \\ \beta^{-} \ 0.6; \ 0.8 \\ \gamma \ 364; \ 637; \\ 284; \ g \\ \sigma \ \sim 0.7 \end{array}$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c} I \ 1 \ 3 \\ \hline 9 \ s \\ \hline 9 \ r \\ 1 \ 2 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\$	$\begin{array}{c c} 1 & 1 & 34 \\ \hline \textbf{3.5 m} & \textbf{52.0} \\ \textbf{1}\gamma 272; \\ 44 & \beta^- 1.3; \\ \beta^- 2.5 & 2.4 \\ \gamma 847; & \gamma 847; \\ 884; 234 & 884 \\ \end{array}$	l 135 6.61 h 5 1.5; 2.2 5 260; 1132; 15 5: 1458 g; m		
τe 121 4 d 16.8 d 2 φ 502 508	Te 122 2.55 σ 0.4 + 3	Te 123 0.89 ¹ γ159 ε ^{• fn 0} γ σ _{n α} 0.00005	Te 124 4.74	Te 125 57.4 d 7.07 μ _e (35)	Te 126 18.84 σ0.12 + 0.8	Te 127 10 9.35 h Γγ(88) β ⁻ 0.7 γ(58) β ⁻ 0.7 γ(58) γ 418	Te 128 31.74 7.2 · 10 ²⁴ a ^{2β⁻} σ 0.03 + 0.2	Te 129 33.6 d 69.6 m ^μ γ (106) β ⁻¹ .5 g ⁻¹ .6 480; γ 696. 197.	$\begin{array}{c} \text{Te 130} \\ 34.08 \\ 2.7 \cdot 10^{21} \\ } \\ \sigma \ 0.01 + 0.19 \end{array}$	Te .0 30 h .0 a β=0.5; 2.5' .0 γ774; 852 β=2.1 γ150; 1γ182 γ150; 452	Te 132 76.3 h	$\begin{array}{c c} Te & 133 \\ \hline 55. & 12.5 m \\ \beta^{-} 0.7; & \theta^{-} 2.2; \\ 3.3 & \gamma 913; \\ 648; & 405, \\ 648; & 405, \\ \mu 334 & 1333 \end{array}$	$\begin{array}{c} Te \ 1.4 \\ 41.8 \\ p^{-} \ 0.6; \ 0.7 \\ \gamma \ 767; \ 210; \\ 278; \ 79; \ 566 \\ g \end{array}$		
Sb 120 6 d 15.9 m + 71; β; 90, γ 1171 6 γ 1171	Sb 121 57.21 σ 0.4 + 5.8	Pb 122 4.2 m. 2.70 d 1.4; 1.4; μγ 61; ε; β ⁺ , 76 γ 564; 693 4000000000000000000000000000000000000	Sb 123 42.79	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Sb 125 2.77 a ^{β⁻ 0.3; 0.6 γ 428; 601; 636; 463 g; m}	Sb 126 ~11 4 9 4 1 1.9 β ⁻ 666 β ⁻ 6665 μ ⁻ θ ⁻ 445	β 0.9; β	$\begin{array}{c c} Sb & 1.8 \\ \hline 10.0 \ m & 9.0, \\ \beta^- 2.6 & \beta^- 2.0 \\ \gamma 743; & 754; \\ 754; & 754; \\ 314 & 314; \\ \gamma & 527 \end{array}$	Sb 129 17.7 m 4.40 β ⁻ 0.6; 2.2 650; γ 813; 1y 112, 915, 723; m; s γ 813; 915,	h $\begin{array}{c} 3911 & 130\\ 3911 & 6.3 m\\ \beta^{-2}\\ \gamma 840, \\ 793; \\ 331; \\ 793;\\ 182 \end{array}$	Sb 13 23 m β [−] 1.3; 3.0 γ 943; 933; 642 g; m	Sb 132 4.1 m 2.8 m 3.7 β ^{-3.9} 69.9 997; 151; 989	Sb 133 5 m β ⁻ 1.2; 11 γ 1096; 81 2755; 837 g; m		
Sn 119 3 d 8.59	Sn 120 32.58 σ 0.001 + 0.13	121 ~50 a 27.0 h ^{1γ (6)} β ^{-0.35} γ 87 e ⁻ μ ₂ ^{-0.38}	Sn 122 4.63 σ 0.15 + 0.001	Sn 123 40.1 m 129.2 d β ⁻ 1.3 β ⁻ 1.4 γ 160 γ (1089)	Sn 124 5.79 σ 0.13 + 0.004	Sn 125 9.5 m 9.64 d β ⁻ 2.4 γ 1067; 1089; γ332	5n 126 2.3 5 · 10 ⁵ a ^{β⁻ 0.3} γ ⁸⁸ ; 64; 87.	Sin 127 4.1 m 2.1 h β-2.7 γ10, 1096, 823	Sn 12 6.5 s 59.1 β ⁻ 0.7 γ 482; 557; 681 169 m	Sn 129 6.9 m 2.2 m γ2.9 γ645; 761 81	$\begin{array}{c} & 130 \\ \textbf{1.7 m} & \textbf{3.7 m} \\ \beta^- \textbf{4} \\ \gamma^1 \textbf{45}; & 1 \\ 899; & \gamma^1 \textbf{92}; \\ 84; & 780; \\ 311; m & 70; g \end{array}$	$\begin{array}{c c} Sn & 13 \\ \hline 50 \ s & 39 \ s \\ \hline \beta^- 3.4 \\ \gamma 1226; \\ 450; \\ 305; \\ 8^{-3.9} \\ 229 \\ \gamma 798 \end{array}$	Sn 132 39.7 s β ⁻ 1.8 γ 341; 86; 899; 247; 993 9		
In 118 4.4 m 5 s 8 ^{[3 - 1.3;}	In 119 18 m 2.3 m β ^{-2.7}		In 121 3.8 m 23.1 s β ^{-2.5}	In 122 10.8 s 10.3 s β ^{-3.0} β ^{-4.4} μ= s s	In 123 47.8 s 5.98 s β ⁻ 4.5 β ⁻ 3.3;	In 1, 4 3.7 s 3.17 s β ^{-3.7} ; β ^{-4.1} ; 51	In 125 12.2 s 2.3 s β ^{-4.1;}	1n 126 1.64 1.60 s	1.04s β ^{-4.8;} 8-70 B ⁻⁷⁰	D9s 0.72 s 0.84 s 50; 68 β ^{-5.3;} β ^{-5.5;} σ	In 129 0.67s 1.23s 0.61s β ^{-5.4;} β ^{-8.1} 70	130 0.53s β ⁻ 2259 μ1221 11905	In 131 0.32s 0.35s 0.28s β=6.6; β=9.2 β=6.8		

1.5

S	low	s pr	roce	ess	???					Rapid r process					
Ν	l _n <	101	³ cm	⁻³	Intermediate					$N_n > 10^{20} cm^{-3}$					
a 126 s 54 s β ⁺ γ256; 455	La 12/ 5.1 m 3.8 m β ⁺ 25	La 128 <1.4 m 5.18 m β ⁺ β ⁺ γ 284; γ 284; 659 679	La 129 11.6 m β ⁺ 2.4; 2.7 γ 279; 111; 254; 457 9	La 130 8.7 m ^{β+} _{γ 357; 551;} _{544; 908}	<i>i</i> process!					135 4 h 8)	La 130 9.9 m ⁵ 3 ⁺ 1.9 γ 819; (761; 1323)	La 137 6 · 10 ⁴ a	La 138 0.090 1.05 · 10 ¹¹ a ε; β ⁻ 0.3 γ 1436; 789 σ 57	La 139 99.910 _{09.2}	
a 125 m 3.5 m β ^{+ 3.4}	Ba 126 100 m	Ba 127 1.9 s 12.7 m β ⁺ 2.4	Ba 128 2.43 d	Ba 129 2.13 h 2.20 h ε β ⁺ 1.4	Ba 130 0.106	Ba 131 14.5 m 11.5 d ^{β+}	Ba 132 0.101	Ba 133 38.9 h 10.5 a ¹ γ 276; 12 5	Ba 2.4	134 17	Ba 135 28.7 h 6.592	Ba 136 7.854	Ba 137 2.55 m 11.232	Ba 138 71.698	
γ /8; 141; 85 S 124 s 30.8 s β ⁺ 4.9		^{γ 181;} 24 66 Cs 126 1.6 m	Cs 127 6.25 h ^ε ^{β+} 0.7; 1.1	y 182; y 214; 1459; 221 202 Cs 128 3.8 m	σ1+8 Cs 129 32.06 h	Y 106; Y 495; 79 124; e ⁻ 216 Cs 130 3.46 m 29.21 m ↓ 80; € 51: €	σ 0.84 + 9.7 Cs 131 9.69 d ^ε no β ⁺	e γ 3305, θ1;303 γ(633) σ4 Cs 132 6.47 d ε; β ⁺ β ⁻ 0.8	σ0.1 + ⁻ Cs ⁻ 10	1.3 133 00	2268 Cs 134 2. h 2.06 a β [−] 0.7 γ605; 796	σ 0.010 + 0.44 Cs 135 5. 2 \cdot 10 ⁶ a	ly 662 σ 5 CS 136 19 s 13.16 d β ^{-0.3;} 0.7 9 819:	σ 0.41 Cs 137 30.17 a β 0.5; 1.2	
e 123 2.08 h	412 9 Xe 124 0.0952	γ 389; 491; 925 Xe 125 57 s 16.9 h ε; β ⁺ γ 188;	Xe 126 0.0890	β ⁺ 2.9 γ 443; 527 Xe 127 70 s 36.4 d ε	γ 372; 411; 549; g Xe 128 1.9102	τ β - 0.4 τ γ 536. Xe 129 8.89 d 26,4006	Xe 130 4.0710	$\begin{array}{c} \gamma 668; 465; 630, \\ \sigma_{n, \alpha} < 0.15 \end{array}$	σ 2.7 + 2 Xe 26.9	27.5 132 086	y 127 ^{β+} _{σ140} Xe 133 2.1 5.25 d ^{β-0.3}	^{ly 781;} ^g 8.3 Xe 134 10.4357	y 1048 y 1048 σ 1.3 Ye 135 15.3 9.10 h hy 527 h 9	m; g	
9; 178; 1 122 3.6 m	σ 28 + 137 I 123 13.2 h	$\begin{array}{c} {}^{1\gamma112;}_{140} & {}^{243;}_{55}_{\sigma_{n,\alpha} \sim 0.02} \\ \\ I \ 124 \\ 4.15 \ d \end{array}$	σ 0.45 + 3.0 <mark>I 125</mark> 59.41 d	$\begin{array}{c} \gamma 203;\\ 172; 375\\ \sigma_{n,\alpha} < 0.0^{\circ}\\ 1126\\ 13.11 \end{array}$	σ 0.48 + 4.7. Ι 127 100	ly 40; 197 e σ 22 I 128 . 5.0 m	σ ^{0.45} + 4.35 I 129 1.57 · 10 ⁷ a	ly 164 e ⁻ σ 90 I 130 9.0 m 12.36 h	σ 0.05 + I 1 8.0	0.40 31 2 d	γ 233 γ 81 e ⁻ 190 1132 83.6 m 2.30 h	σ 0.003 + 0.26 I 133 9 s 20.8 h	$ \begin{array}{c} \beta^{-} \dots \\ \gamma (787) \\ g \end{array} \begin{array}{c} \gamma 22 \\ 608 \dots \\ \sigma 2.65 \cdot 10 \\ \hline 1 134 \\ 3.5 m \\ 52.0 \end{array} $	σ 0.26 ' 135 1 h	
4 e 121	^ε no β ⁺ γ 159 g Te 122	^ε β ⁺ 2.1 γ 603; 1691; 723 Te 123	¢ γ 35; e ⁻ g σ 900 Te 124	ε; β ⁻ 0.9; 1.3 β ⁺ 1.1 γ 389; 666 σ 5960	σ 6.2 Te 126	ε; β ⁺ γ 443; 527 σ 22 Te 127	γ40 e ⁻ ;g σ20.7 + 10.3 Te 128	e ⁻ γ 536; β ⁻ 2.5 669; 739 γ 536 σ 18 Te 129	γ 364; 6 284; 9 σ~0.7	^{37;} 130	668; 773; 600; 175 Te	^{ly 913;} 647; 73 Te 132	44 β ⁻ 2.5 γ 847; 884; 234 Te 133	10267 (132; 16 1458 g; m Te 134	
d 16.8 d ε γ 573; 508	2.55 σ 0.4 + 3	0.89 10 ¹³ a 6; no y o 370 o 370 o 1000000	4.74 σ1+6	57.4 d 7.07 ^Ι γ (35) e ⁻ σ 1.1	18.84 σ 0.12 + 0.8	10 e ⁻ β ⁻ 0.7 γ (58) 9.35 h 9.35 h 9.35 h 9.35 h	31.74 7.2 · 10 ²⁴ a ^{2β⁻} σ 0.03 + 0.2	33.6 d 69.6 m Ιγ (106) β ⁻⁺ 1.5 e ⁻ γ 28; β ⁻⁺ 1.6 460; γ 696 197	34. 2.7 · ⁻ ^{2β⁻} σ 0.01 +	.08 10 ²¹ a	30 h β ⁻ 0.5; 2.5 y 774; β ⁻ 2.1 y 150; y 182 452	76.3 h μ.0.2 γ2.1.50 g	$\begin{array}{c cccc} \textbf{55.} & \textbf{12.5 m} \\ \beta^{-} \ 0.7; & \beta^{-} \ 2.2; \\ \textbf{3.3} \\ \gamma \ 913; & \textbf{7.}. \\ 648; \ g \\ l_{\gamma} \ 334 & \textbf{1333} \end{array}$	41.8 m β ⁻ 0.6; 0.7 γ 767; 210; 278; 79; 566 g	
b 120 d 15.9 m $\frac{1}{10} \frac{1}{10} \frac{1}$	Sb 121 57.21	Cb 122 4.2 m 2.70 d 1.4; 1.4; ½0 2.0 1/γ 61; ~ 76 γ 564;	Sb 123 42.79 ^{or} 0.02 + 0.04 + 4.0	Sb 124 20 m 1.6 m 60.3 d I _γ (11) β ^{-0.6} 2.3 β ^{-1.2} γ603; 1691 y(05) γ605; 1691	Sb 125 2.77 a β ⁻ 0.3; 0.6 γ 428; 601; 636; 463 α; m	Sb 126 ~11 1.9 12.4 d p 0.5 1.9 4 1 1.9 666 666; 1y (23) 1y (16) 41	β 0.9; γ 686; 473, γ 684 α: m	$\begin{array}{c c} Sb & 1.8 \\ \hline 10.0 m & 9.0 \\ \beta^- 2.6 & \beta^- 2.0 \\ \gamma^743; & \gamma^743; \\ 754; & 754; \\ 314 & 314; \\ y & 527 \end{array}$	Sb 17.7 m 650; 650; 19;112; 723; m2);	129 4.40 h β ⁻ 0.6; μ 2.2 γ 813; 5 915 c; m	39 39 39 5 39 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 30 5 5 5 5 5 5 5 5	Sb 13 23 m β ⁻ 1.3; 3.0 γ 943; 933; 642 3; m	Sb 132 4.1 m 2.8 m -3.7 β ⁻ 3.9 697, 151; 697; 1697; 104 989	Sb 133 15 m β [−] 1.2; 11 γ 1096; 81 2755; 837 α: m	
in 119 d 8.59	Sn 120 32.58	50 a 27.0 h ¹ γ(6) β ^{-0.35} γ.87 β ^{-0.38}	Sn 122 4.63	Sn 123 40.1 m 129.2 d β ⁻ 1.3 β ⁻ 1.4	Sn 124 5.79	Sn 125 9.5 m 9.64 d β ⁻ 2.4 γ 1067; γ.99; 9.20	Sn 126 2.3 5 · 10 ⁵ a ^{β⁻ 0.3} γ88; 64; 87.	5 127 4.1 m 2.1 h β ⁻ 2.7 1096; γ.491 893	Sn 6.5 s	$\begin{array}{c} \textbf{12}\\ \textbf{59.1}\\ \textbf{m}\\ \beta^{-}\ 0.7\\ \gamma\ 482;\ 75;\\ 557;\\ 681\\ \textbf{m} \end{array}$	Sn 129 6.9 m 2.9 112. π 5 3.3 γ 645; 81 π	$\begin{array}{c c} & \textbf{130} \\ \textbf{1.7 m} & \textbf{3.7 m} \\ \textbf{\beta}^{-} & \textbf{-4} \\ \gamma 145; \\ \textbf{399;} & \gamma 192 \\ \textbf{344;} & \textbf{700;} \\ \textbf{311, 700;} \end{array}$	Sn 13 50 s 39 s β ⁻ 3.4 30 s γ 1226; 450; 305; β ⁻ 3.9 229, y 768	Sn 132 39.7 s β ⁻ 1.8 γ 341; 86; 899; 247; 993 9	
n 118 4.4 m 5 s β ⁻ 1.3;	In 119 18 m 2.3 m β ⁻ 2.7	In 120 47.3 s 46.2 s 3.1 s β ^{-2.1} β ^{-2.2} ;	In 121 3.8 m 23.1 s β ⁻ 2.5	$\frac{\ln 122}{10.8 \text{ s} 10.3 \text{ s}} 1.5 \text{ s}$	In 123 47.8 s 5.98 s β ⁻ 4.5 β ⁻ 3.3;	In 1, 4 3.7 s 3.17 s β ^{-3.7} ; β ^{-4.1} ;	In 125 12.2 s 2.3 s β ⁻ 4.1;	in 126 1.64 1.60 s	1.04s 3. β ⁻ 4.8;	127 1.09s	In 120 0.72 s 0.84 s ^{p-5.3;} ^{p-5.5;}	In 129 0.67s 1.23s 0.61s β ^{-5.4;} στοι β ^{-5.7;}	130 0.53s 0.1 0.33s β ⁻	In 131 0.32s 0.35s 0.28s β ⁻ 6.6; β ⁻ 9.2 β ⁻ 6.8	

Observational evidence that it must happen in some stars...



Hampel et al. (2016, 2019)

massive stars: core collapse supernovae (He burning)

low-mass stars: giant star winds (He burning)

Big Bang

every star: winds and explosions (H burning)

Human Body Ingredients

The four ingredients below are essential parts of the body's protein, carbohydrate and fat architecture.



65.0% Critical to the conversion of food into energy.

CARBON 18.5% The so-called backbone of the building blocks of the body and a key part of other important compounds, such as testosterone and estrogen.

HYDROGEN 9.5%

Η

Helps transport nutrients, remove wastes and regulate body temperature. Also plays an important role in energy production.



NITROGEN

Found in amino acids, the building blocks of proteins; an essential part of the nucleic acids that constitute DNA.

(Percentage of body weight. Source: Biology, Campbell and Reece, eighth edition.)

Other Key Elements

Calcium 1.5% Lends rigidity and strength to bones and teeth; also important for the functioning of nerves and muscles, and for blood clotting.

Phosphorus 1.0% Needed for building and maintaining bones and teeth; also found in the molecule ATP (adenosine triphosphate), which provides energy that drives chemical reactions in cells

Potassium 0.4% Important for electrical signaling in nerves and maintaining the balance of water in the body.

Sulfur 0.3% Found in cartilage, insulin (the hormone that enables the body to use sugar), breast milk, proteins that play a role in the immune system, and keratin, a substance in skin, hair and nails.

Chlorine 0.2% Needed by nerves to function properly; also helps produce gastric juices.

Sodium 0.2% Plays a critical role in nerves' electrical signaling; also helps regulate the amount of water in the body.

Magnesium 0.1% Plays an important role in the structure of the skeleton and muscles; also found in molecules that help enzymes use ATP to supply energy for chemical reactions in cells

Iodine (trace amount) Part of an essential hormone produced by the thyroid gland; regulates metabolism.

Iron (trace amount) Part of hemoglobin, which carries oxygen in red blood cells.

Zinc (trace amount) Forms part of some enzymes involved in digestion. Ca, P, K, S, Cl, Na, Mg

massive stars: core collapse supernovae (C, Ne, O burning)

> neutron star mergers (*r* process)

Fe, Zn White dwarf supernovae (NSE process)

Recommended Review papers

REVIEW ARTICLE

Constraining the astrophysical origin of the p-nuclei through nuclear physics and meteoritic data

T Rauscher^{1,2,3}, N Dauphas⁴, I Dillmann^{5,6}, C Fröhlich⁷, Zs Fülöp² and Gy Gyürky² Published 10 May 2013 • 2013 IOP Publishing Ltd <u>Reports on Progress in Physics</u>, <u>Volume 76</u>, <u>Number 6</u>

International Journal of Modern Physics E | Vol. 25, No. 04, 1630003 (2016)

| Review Article

The production of proton-rich isotopes beyond iron: The γ -process in stars

No Acce

Marco Pignatari, Kathrin Göbel, René Reifarth and Claudia Travaglio



Progress in Particle and Nuclear Physics Volume 107, July 2019, Pages 109-166



Review

Current status of *r*-process nucleosynthesis

T. Kajino ^{a, b, c}⊠, W. Aoki ^a⊠, A.B. Balantekin ^{a, d}⊠, R. Diehl ^{e, f}⊠, M.A. Famiano ^{a,} ^g ♀ ⊠, G.J. Mathews ^{a, h} ⊠



Access Provided by Chinese Academy of Sciences - Institute of Modern Physics

JOURNALS A-Z JOURNAL INFO

PRICING & SUBSCRIPTIC

Home / Annual Review of Nuclear and Particle Science / Volume 66, 2016 / Janka, pp 341-375

Physics of Core-Collapse Supernovae in Three Dimensions: A Sneak Preview

Annual Review of Nuclear and Particle Science

Vol. 66:341-375 (Volume publication date October 2016) https://doi.org/10.1146/annurev-nucl-102115-044747

Hans-Thomas Janka,¹ Tobias Melson,^{1,2} and Alexander Summa¹

Publications of the Astronomical Society of Australia Article Metrics Volume 31 e030

The Dawes Review 2: Nucleosynthesis and Stellar Yields of Low- and Intermediate-Mass Single Stars

Amanda I. Karakas ^(a1) and John C. Lattanzio ^(a2) 🕀

DOI: https://doi.org/10.1017/pasa.2014.21 Published online by Cambridge University Press: 22 July 2014 NASA ADS Abstraction



Progress in Particle and Nuclear Physics Volume 102, September 2018, Pages 1-47



Radioactive nuclei from cosmochronology to habitability

This paper is dedicated to the memory of Gerald J. Wasserburg, who pioneered, built up, and inspired the science presented here.

M. Lugaro ^{a, b} ペ ⊠, U. Ott ^{c, d}, Á. Kereszturi ^a