Nuclei in the Cosmos School
2025

STELLAR EVOLUTION

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1869

Dmitrij Ivanovič Mendeleev

63 known elements

He grouped the elements according to their chemical properties and ordered them in increasing mass (more or less)

Reihen	Gruppe I. — R^2O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	— =44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63
5	(Cu=63)	Zn=65	— =68	— =72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	— =100	Ru=104, Rh=104, Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

He argues that the mass difference between two consecutive nuclei in his table amounts to 2 atomic masses

Periodic Table of the Elements

Atomic Number → 13 ← Symbol Al
Name → Aluminium
Atomic Weight 26.982
Electrons per shell → 2-8-3

State of matter (color of name)
GAS LIQUID SOLID UNKNOWN

Subcategory in the metal-metalloid-nonmetal trend (color of background)
- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Unknown chemical properties

58.93 58.7

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008 1																	2 He Helium 4.0026 2
3 Li Lithium 6.94 2-1	4 Be Beryllium 9.0122 2-2											5 B Boron 10.81 2-3	6 C Carbon 12.011 2-4	7 N Nitrogen 14.007 2-5	8 O Oxygen 15.999 2-6	9 F Fluorine 18.998 2-7	10 Ne Neon 20.180 2-8
11 Na Sodium 22.98976928 2-8-1	12 Mg Magnesium 24.305 2-8-2											13 Al Aluminium 26.982 2-8-3	14 Si Silicon 28.085 2-8-4	15 P Phosphorus 30.974 2-8-5	16 S Sulfur 32.06 2-8-6	17 Cl Chlorine 35.45 2-8-7	18 Ar Argon 39.948 2-8-8
19 K Potassium 39.0983 2-8-8-1	20 Ca Calcium 40.078 2-8-8-2	21 Sc Scandium 44.955908 2-8-9-2	22 Ti Titanium 47.867 2-8-10-2	23 V Vanadium 50.9415 2-8-11-2	24 Cr Chromium 51.9961 2-8-13-1	25 Mn Manganese 54.938044 2-8-13-2	26 Fe Iron 55.845 2-8-14-2	27 Co Cobalt 58.933 2-8-15-2	28 Ni Nickel 58.693 2-8-16-2	29 Cu Copper 63.546 2-8-18-1	30 Zn Zinc 65.38 2-8-18-2	31 Ga Gallium 69.723 2-8-18-3	32 Ge Germanium 72.630 2-8-18-4	33 As Arsenic 74.922 2-8-18-5	34 Se Selenium 78.971 2-8-18-6	35 Br Bromine 79.904 2-8-18-7	36 Kr Krypton 83.798 2-8-18-8
37 Rb Rubidium 85.4678 2-8-18-8-1	38 Sr Strontium 87.62 2-8-18-8-2	39 Y Yttrium 88.90584 2-8-18-9-2	40 Zr Zirconium 91.224 2-8-18-10-2	41 Nb Niobium 92.90637 2-8-18-12-1	42 Mo Molybdenum 95.95 2-8-18-13-1	43 Tc Technetium (98) 2-8-18-13-2	44 Ru Ruthenium 101.07 2-8-18-15-1	45 Rh Rhodium 102.91 2-8-18-16-1	46 Pd Palladium 106.42 2-8-18-18	47 Ag Silver 107.87 2-8-18-18-1	48 Cd Cadmium 112.41 2-8-18-18-2	49 In Indium 114.82 2-8-18-18-3	50 Sn Tin 118.71 2-8-18-18-4	51 Sb Antimony 121.76 2-8-18-18-5	52 Te Tellurium 127.60 2-8-18-18-6	53 I Iodine 126.90 2-8-18-18-7	54 Xe Xenon 131.29 2-8-18-18-8
55 Cs Caesium 132.90545196 2-8-18-18-8-1	56 Ba Barium 137.327 2-8-18-18-8-2	57-71 Lanthanides	72 Hf Hafnium 178.49 2-8-18-32-10-2	73 Ta Tantalum 180.94788 2-8-18-32-11-2	74 W Tungsten 183.84 2-8-18-32-12-2	75 Re Rhenium 186.21 2-8-18-32-13-2	76 Os Osmium 190.23 2-8-18-32-14-2	77 Ir Iridium 192.22 2-8-18-32-15-2	78 Pt Platinum 195.08 2-8-18-32-17-1	79 Au Gold 196.97 2-8-18-32-18-1	80 Hg Mercury 200.59 2-8-18-32-18-2	81 Tl Thallium 204.38 2-8-18-32-18-3	82 Pb Lead 207.2 2-8-18-32-18-4	83 Bi Bismuth 208.98 2-8-18-32-18-5	84 Po Polonium (209) 2-8-18-32-18-6	85 At Astatine (210) 2-8-18-32-18-7	86 Rn Radon (222) 2-8-18-32-18-8
87 Fr Francium (223) 2-8-18-32-18-8-1	88 Ra Radium (226) 2-8-18-32-18-8-2	89-103 Actinides	104 Rf Rutherfordium (267) 2-8-18-32-32-10-2	105 Db Dubnium (268) 2-8-18-32-32-11-2	106 Sg Seaborgium (269) 2-8-18-32-32-12-2	107 Bh Bohrium (270) 2-8-18-32-32-13-2	108 Hs Hassium (277) 2-8-18-32-32-14-2	109 Mt Meitnerium (278) 2-8-18-32-32-15-2	110 Ds Darmstadtium (281) 2-8-18-32-32-17-1	111 Rg Roentgenium (282) 2-8-18-32-32-17-2	112 Cn Copernicium (285) 2-8-18-32-32-18-2	113 Nh Nihonium (286) 2-8-18-32-32-18-3	114 Fl Flerovium (289) 2-8-18-32-32-18-4	115 Mc Moscovium (290) 2-8-18-32-32-18-5	116 Lv Livermorium (293) 2-8-18-32-32-18-6	117 Ts Tennessine (294) 2-8-18-32-32-18-7	118 Og Oganesson (294) 2-8-18-32-32-18-8
		57 La Lanthanum 138.91 2-8-18-18-9-2	58 Ce Cerium 140.12 2-8-18-19-9-2	59 Pr Praseodymium 140.91 2-8-18-21-8-2	60 Nd Neodymium 144.24 2-8-18-22-8-2	61 Pm Promethium (145) 2-8-18-23-8-2	62 Sm Samarium 150.36 2-8-18-24-8-2	63 Eu Europium 151.96 2-8-18-25-8-2	64 Gd Gadolinium 157.25 2-8-18-25-9-2	65 Tb Terbium 158.93 2-8-18-27-8-2	66 Dy Dysprosium 162.50 2-8-18-28-8-2	67 Ho Holmium 164.93 2-8-18-29-8-2	68 Er Erbium 167.26 2-8-18-30-8-2	69 Tm Thulium 168.93 2-8-18-31-8-2	70 Yb Ytterbium 173.05 2-8-18-32-8-2	71 Lu Lutetium 174.97 2-8-18-32-9-2	
		89 Ac Actinium (227) 2-8-18-32-18-9-2	90 Th Thorium 232.04 2-8-18-32-18-10-2	91 Pa Protactinium 231.04 2-8-18-32-20-9-2	92 U Uranium 238.03 2-8-18-32-21-9-2	93 Np Neptunium (237) 2-8-18-32-22-9-2	94 Pu Plutonium (244) 2-8-18-32-24-8-2	95 Am Americium (243) 2-8-18-32-25-8-2	96 Cm Curium (247) 2-8-18-32-25-9-2	97 Bk Berkelium (247) 2-8-18-32-27-8-2	98 Cf Californium (251) 2-8-18-32-28-8-2	99 Es Einsteinium (252) 2-8-18-32-29-8-2	100 Fm Fermium (257) 2-8-18-32-30-8-2	101 Md Mendelevium (258) 2-8-18-32-31-8-2	102 No Nobelium (259) 2-8-18-32-32-8-2	103 Lr Lawrencium (266) 2-8-18-32-32-8-3	

1911/13

He suggests a link between atomic mass and "intra-atomic" charge: If the masses of two consecutive elements in the Mendeleev table differ by a fixed value of two, and the "intra-atomic" charge is half the mass, it follows that the position in the Mendeleev table equates the "intra-atomic charge"

Antonius Johannes van den Broek

PROBLEM: such a relation is certainly wrong for the Uranium

Intra-atomic Charge.

In a previous letter to Nature (July 20, 1911, p. 78) the hypothesis was proposed that the atomic weight being equal to about twice the intra-atomic charge, "to each possible intra-atomic charge corresponds a possible element," or that (*Phys. Zeitschr.*, xiv., 1912, p. 39), "if all elements be arranged in order of increasing atomic weights, the number of each element in that series must be equal to its intra-atomic charge."

Charges being known only very roughly (probably correct to 20 per cent.), and the number of the last element Ur in the series not being equal even approximately to half its atomic weight, either the number of elements in Mendeléeff's system is not correct (that was supposed to be the case in the first letter), or the intra-atomic charge for the elements at the end of the series is much smaller than that deduced from experiment (about 100 for Au).

Now, according to Rutherford, the ratio of the scattering of α particles per atom divided by the square of the charge must be constant. Geiger and Marsden (*Phil. Mag.*, xxv., pp. 617 and 618, notes

Henry Gwyn Jeffreys Moseley

Frederick Soddy

1911

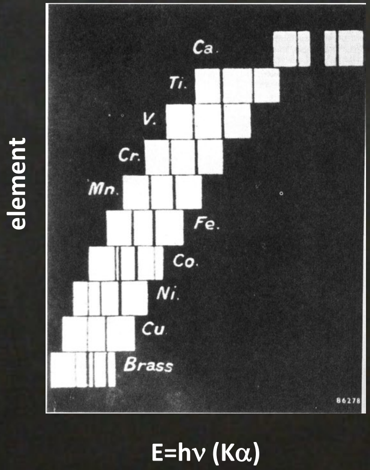
Frederick Soddy

Chemical homogeneity is no longer a guarantee that any supposed element is not a mixture of several different atomic weights, or that any atomic weight is not merely a mean number. The constancy of atomic weight, whatever the source of the material, is not a complete proof of homogeneity

1913 December

Henry Gwyn Jeffreys Moseley

Moseley's empirical law => $E \approx (N-1)^2$

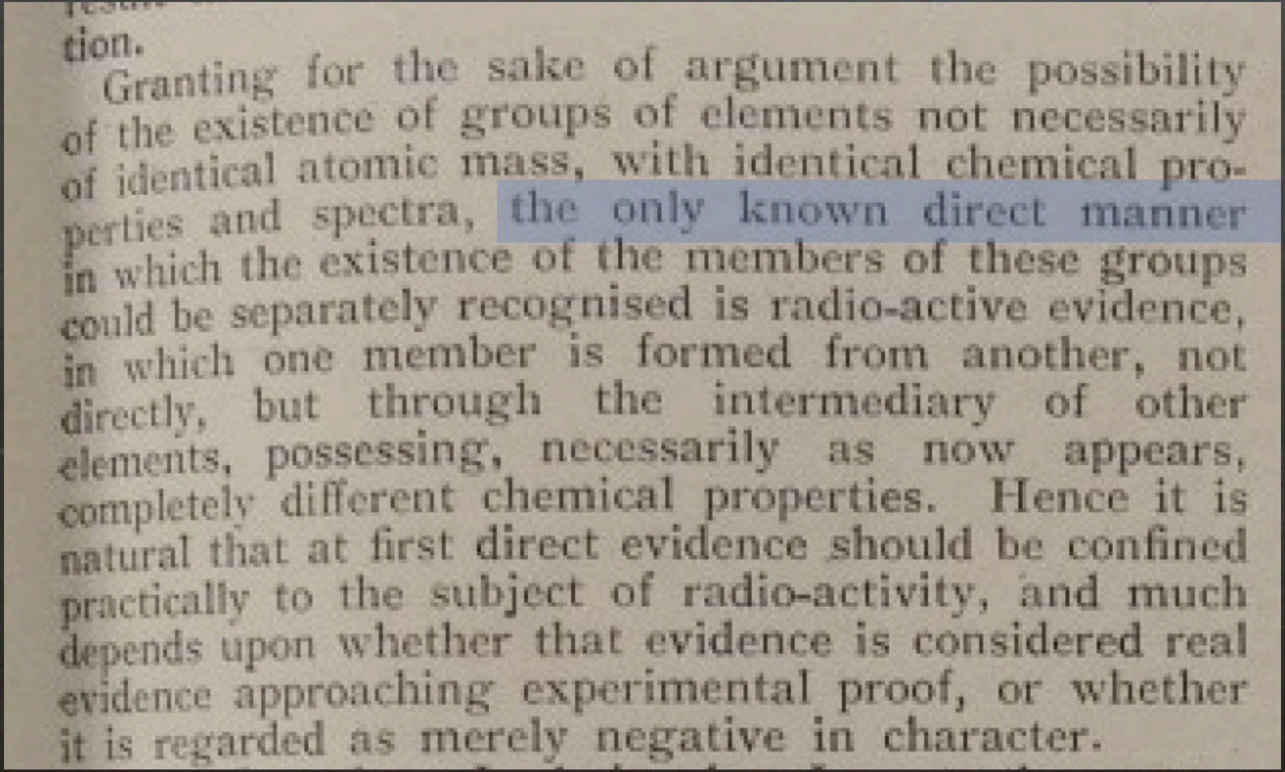


already have definite proof. Rutherford has shown, from the magnitude of the scattering of α particles by matter, that this nucleus carries a + charge approximately equal to that of $\frac{A}{2}$ electrons, where A is the atomic weight. Barkla, from the scattering of X rays by matter, has shown that the number of electrons in an atom is roughly $\frac{A}{2}$, which for an electrically neutral atom comes to the same thing. Now atomic weights increase on the average by about 2 units at a time, and this strongly suggests the view that N increases from atom to atom always by a single electronic unit. We are therefore led by experiment to the view that N is the same as the number of the place occupied by the element in the periodic system. This atomic number is then for H 1 for He 2 for Li 3 . . . for Ca 20 . . . for Zn 30, &c. This theory was originated by Broek † and since used by Bohr ‡. We can confidently predict that in the few cases in which the order of the atomic weights A clashes with the chemical order of the periodic system, the chemical properties are governed by N; while A is itself probably a complicated function of N. The very close similarity between the

1913

He suggests to use radioactive nuclei to check for the existence of group of elements that share the same chemical properties but have different masses

Frederick Soddy

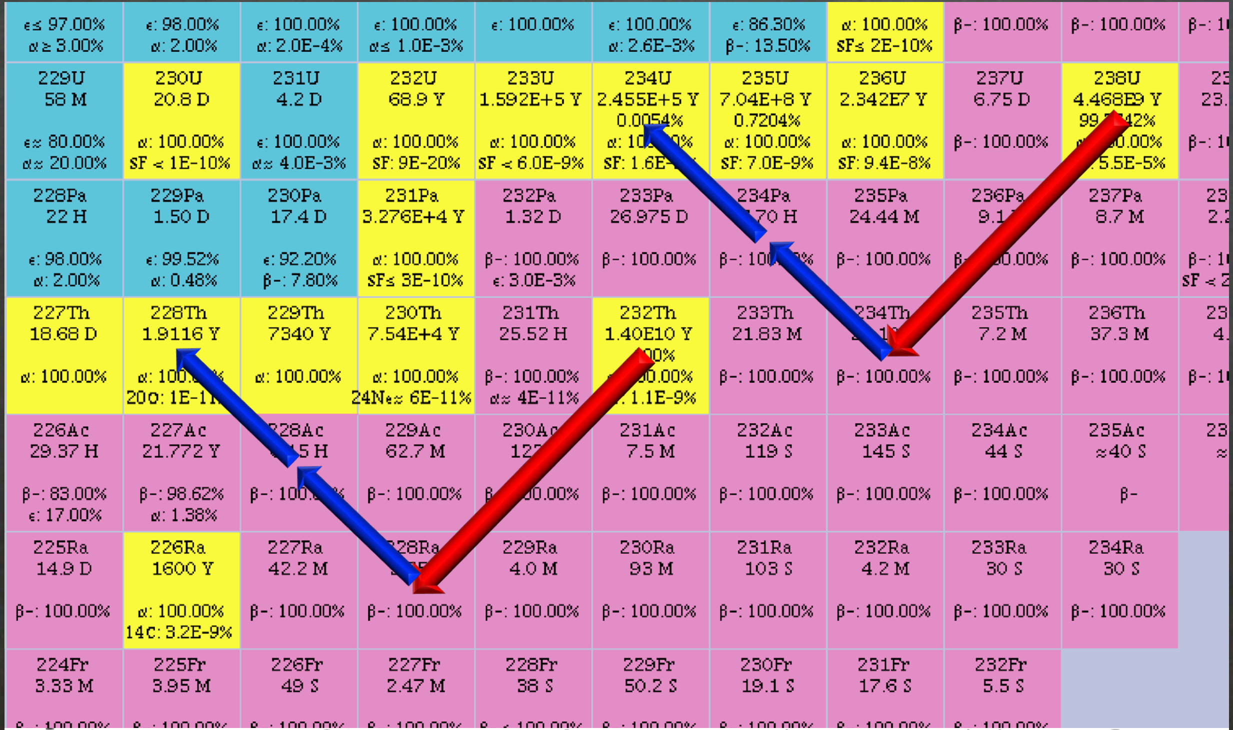


tion.

Granting for the sake of argument the possibility of the existence of groups of elements not necessarily of identical atomic mass, with identical chemical properties and spectra, the only known direct manner in which the existence of the members of these groups could be separately recognised is radio-active evidence, in which one member is formed from another, not directly, but through the intermediary of other elements, possessing, necessarily as now appears, completely different chemical properties. Hence it is natural that at first direct evidence should be confined practically to the subject of radio-activity, and much depends upon whether that evidence is considered real evidence approaching experimental proof, or whether it is regarded as merely negative in character.

1913

Frederick Soddy



ε≤ 97.00% α≥ 3.00%	ε: 98.00% α: 2.00%	ε: 100.00% α: 2.0E-4%	ε: 100.00% α≤ 1.0E-3%	ε: 100.00%	ε: 100.00% α: 2.6E-3%	ε: 86.30% β-: 13.50%	α: 100.00% SF≤ 2E-10%	β-: 100.00%	β-: 100.00%	β-: 1
229U 58 M ε≈ 80.00% α≈ 20.00%	230U 20.8 D α: 100.00% SF < 1E-10%	231U 4.2 D ε: 100.00% α≈ 4.0E-3%	232U 68.9 Y α: 100.00% SF: 9E-20%	233U 1.592E+5 Y α: 100.00% SF < 6.0E-9%	234U 2.455E+5 Y 0.0054% α: 10[illegible]% SF: 1.6E-[illegible]	235U 7.04E+8 Y 0.7204% α: 100.00% SF: 7.0E-9%	236U 2.342E7 Y α: 100.00% SF: 9.4E-8%	237U 6.75 D β-: 100.00%	238U 4.468E9 Y 99.[illegible]42% [illegible]0.00% [illegible]5.5E-5%	23 23. β-: 1
228Pa 22 H ε: 98.00% α: 2.00%	229Pa 1.50 D ε: 99.52% α: 0.48%	230Pa 17.4 D ε: 92.20% β-: 7.80%	231Pa 3.276E+4 Y α: 100.00% SF≤ 3E-10%	232Pa 1.32 D β-: 100.00% ε: 3.0E-3%	233Pa 26.975 D β-: 100.00%	234Pa [illegible]70 H β-: 10[illegible]%	235Pa 24.44 M β-: 100.00%	236Pa 9.1[illegible] β[illegible]0.00%	237Pa 8.7 M β-: 100.00%	23 2.2 β-: 1 SF < 2
227Th 18.68 D α: 100.00%	228Th 1.9116 Y α: 100.[illegible]% 20O: 1E-1[illegible]	229Th 7340 Y α: 100.00%	230Th 7.54E+4 Y α: 100.00% 24Ne≈ 6E-11%	231Th 25.52 H β-: 100.00% α≈ 4E-11%	232Th 1.40E10 Y [illegible]00% [illegible]0.00% [illegible]1.1E-9%	233Th 21.83 M β-: 100.00%	234Th [illegible] β-: 100.00%	235Th 7.2 M β-: 100.00%	236Th 37.3 M β-: 100.00%	23 4. β-: 1
226Ac 29.37 H β-: 83.00% ε: 17.00%	227Ac 21.772 Y β-: 98.62% α: 1.38%	[illegible]28Ac [illegible]5 H β-: 100.[illegible]%	229Ac 62.7 M β-: 100.00%	230Ac 12[illegible] [illegible]00.00%	231Ac 7.5 M β-: 100.00%	232Ac 119 S β-: 100.00%	233Ac 145 S β-: 100.00%	234Ac 44 S β-: 100.00%	235Ac ≈40 S β-	23 ≈
225Ra 14.9 D β-: 100.00%	226Ra 1600 Y α: 100.00% 14C: 3.2E-9%	227Ra 42.2 M β-: 100.00%	[illegible]28Ra [illegible] β-: 100.00%	229Ra 4.0 M β-: 100.00%	230Ra 93 M β-: 100.00%	231Ra 103 S β-: 100.00%	232Ra 4.2 M β-: 100.00%	233Ra 30 S β-: 100.00%	234Ra 30 S β-: 100.00%	
224Fr 3.33 M	225Fr 3.95 M	226Fr 49 S	227Fr 2.47 M	228Fr 38 S	229Fr 50.2 S	230Fr 19.1 S	231Fr 17.6 S	232Fr 5.5 S		

and the periodic law. The successive expulsion of one α and two β particles in three radio-active changes in any order brings the intra-atomic charge of the element back to its initial value, and the element back to its original place in the table, though its atomic mass is reduced by four units. We have recently obtained

1913

Frederick Soddy

Chemical homogeneity is no longer a guarantee that any supposed element is not a mixture of several different atomic weights, or that any atomic weight is not merely a mean number. The constancy of atomic weight, whatever the source of the material, is not a complete proof of homogeneity

1)

I regard van der Broek's view, that the number representing the net positive charge of the nucleus is the number of the place which the element occupies in the periodic table when all the possible places from hydrogen to uranium are arranged in sequence, as practically proved so far as the relative value of the charge for the members of the end of the sequence, from thallium to uranium, is concerned. We are left

2)

little originality in it. The same algebraic sum of the positive and negative charges in the nucleus, when the arithmetical sum is different, gives what I call "isotopes" or "isotopic elements," because they occupy the same place in the periodic table. They are chemically identical, and save only as regards the relatively few physical properties which depend upon atomic mass directly, physically identical also. Unit

1913 April

Frederick Soddy

Jahrbuch der Radioaktivität und Elektronik 1913 Vol. 10, page 193

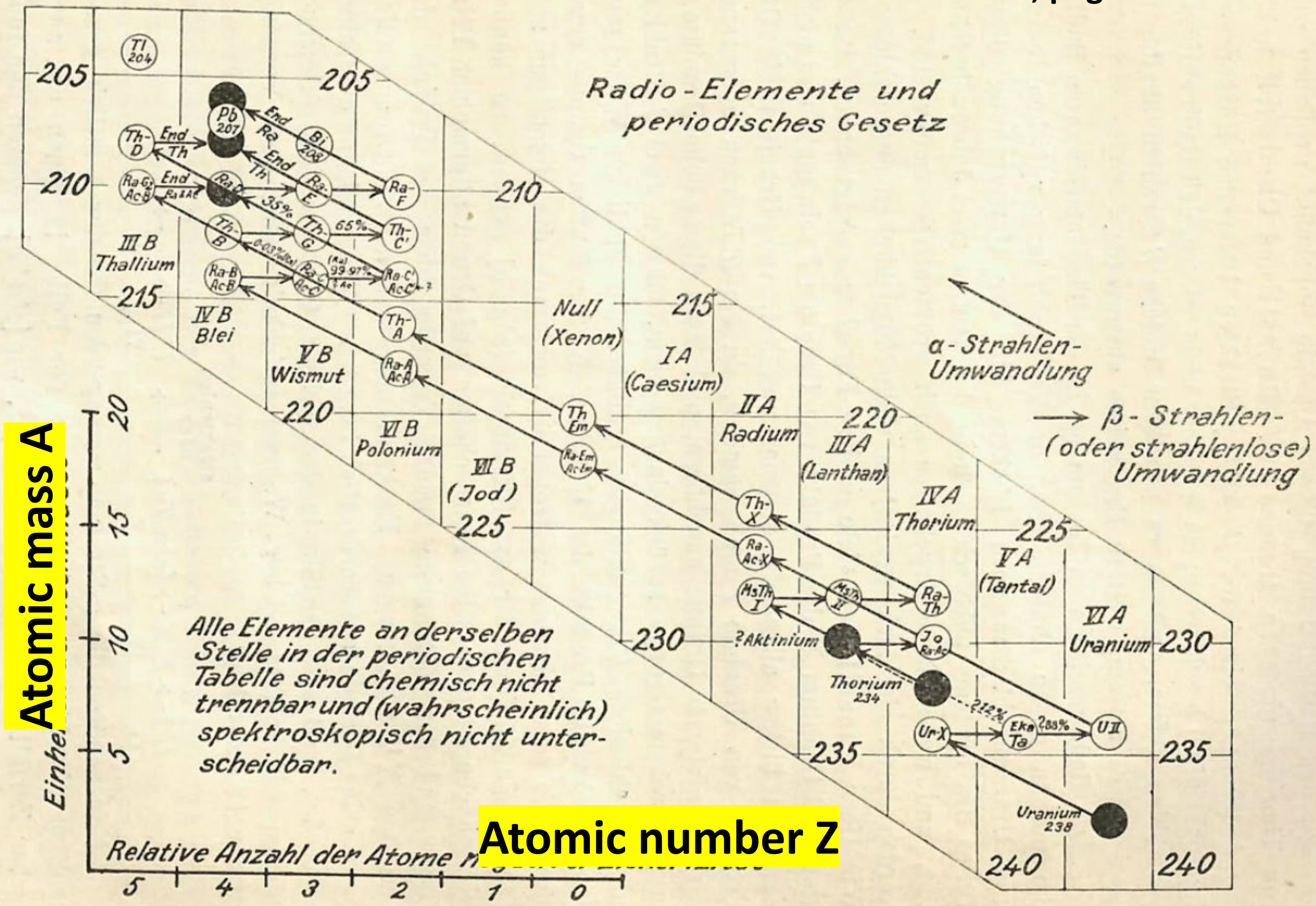
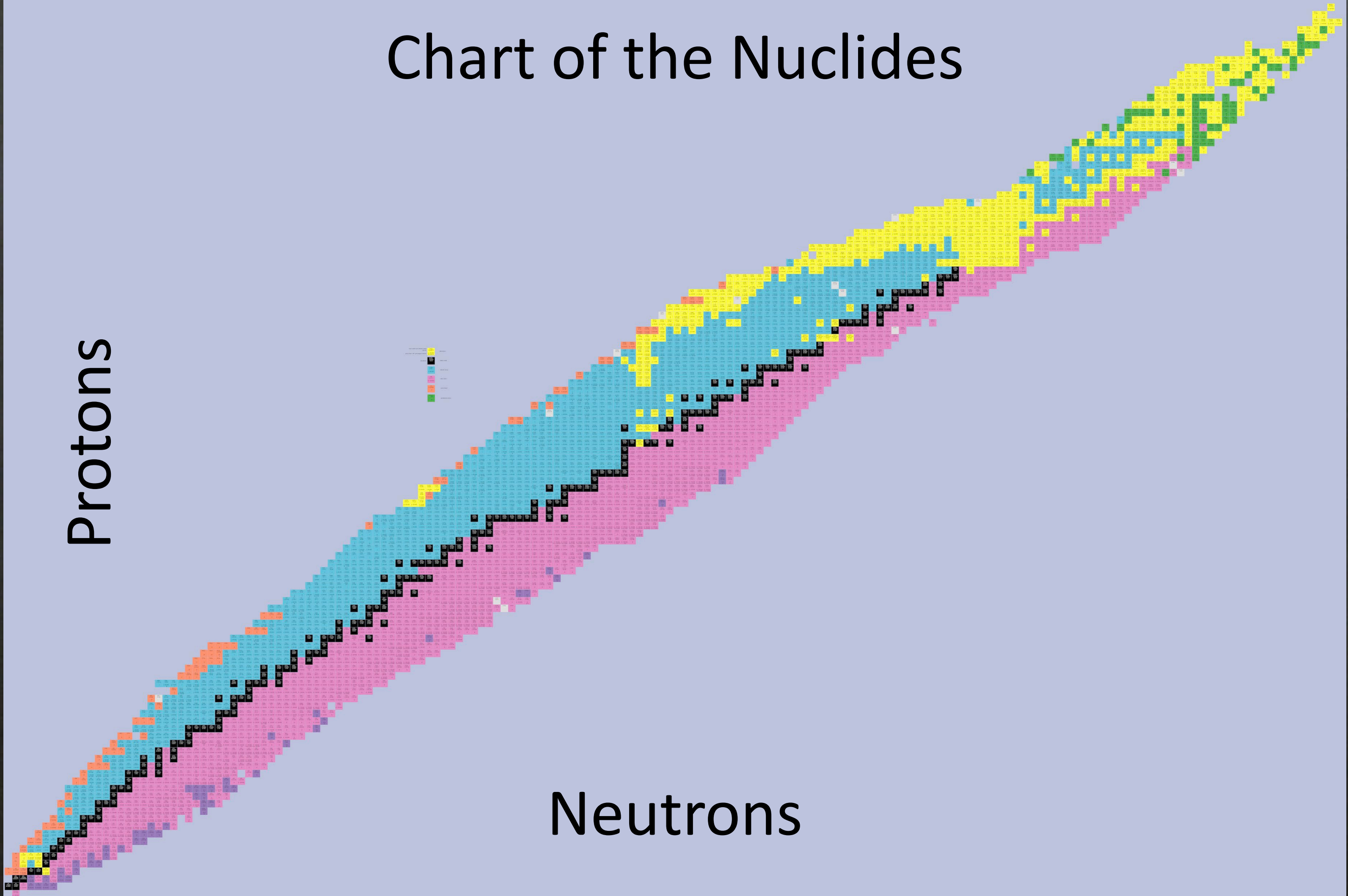
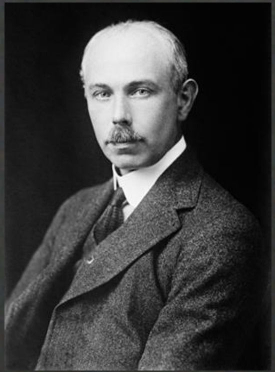


Chart of the Nuclides



1919/1920



Francis William Aston

18 elements analyzed to check for the presence of isotopes

November

Neon.

In response to inquiries, may I use your columns to make two announcements in reference to the above?

First, by making use of a new and more powerful method of positive-ray analysis (the description of which is now in the press), I have succeeded in obtaining measurements of mass and other evidence of sufficient accuracy to prove beyond all dispute that atmospheric neon (atomic weight 20·200, O=16) is a mixture of two isotopes of atomic weights 20·00 and 22·00 correct to about 1/10th per cent.

Secondly, permission to publish being now granted, a full account of recent experiments on "Neon Lamps for Stroboscopic Work" will shortly appear in the Proceedings of the Cambridge Philosophical Society.

F. W. Aston.

Cavendish Laboratory, Cambridge,
November 19.

July 1920

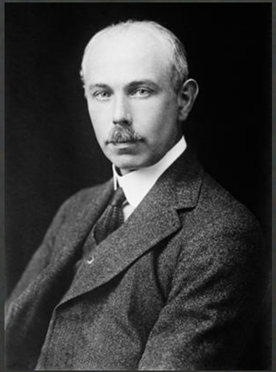
By far the most important result obtained from this work is the generalisation that, with the exception of hydrogen, all the atomic weights of all elements so far measured are exactly whole numbers on the scale O=16 to the accuracy of experiment (1 in 1000). By means of a special

method (see *Phil. Mag.*, May, 1920, p. 621), some results of which are given in spectrum vii., hydrogen is found to be 1·008, which agrees with the value accepted by chemists. This exception from the whole number rule is not unexpected, as on the Rutherford "nucleus" theory the hydrogen atom is the only one not containing any negative electricity in its nucleus.

Ne has two isotopes: A=20 and A=22

All atomic weights are exactly integer numbers, with the exception of H

1927



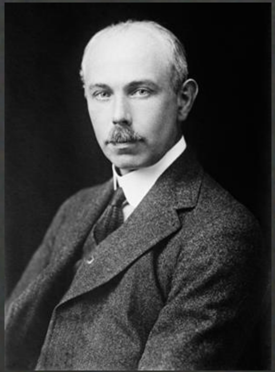
Francis William Aston

... a few years later ***no*** nuclear specie had an atomic mass equal to an integer number...

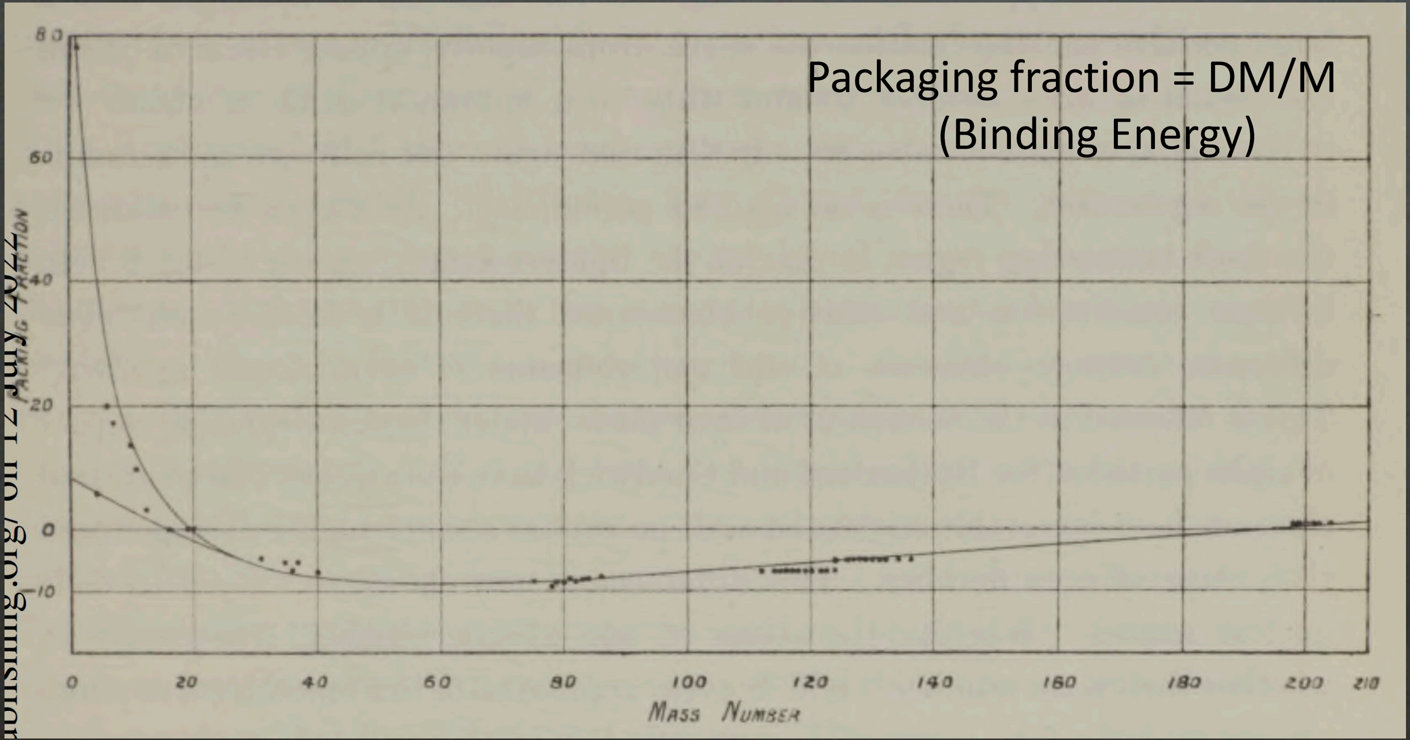
Table II.

Atom.	Packing Fraction $\times 10^4$.	Mass O = 16.	Atom.	Packing Fraction $\times 10^4$.	Mass O = 16.
H	$77 \cdot 8 \pm 1 \cdot 5$	1·00778	Cl^{35}	$-4 \cdot 8 \pm 1 \cdot 5$	34·983
He	$5 \cdot 4 \pm 1$	4·00216	A^{36}	$-6 \cdot 6 \pm 1 \cdot 5$	35·976
Li^{6}	$20 \cdot 0 \pm 3$	6·012	Cl^{37}	$-5 \cdot 0 \pm 1 \cdot 5$	36·980
Li^{7}	$17 \cdot 0 \pm 3$	7·012	A^{40}	$-7 \cdot 2 \pm 1$	39·971
B^{10}	$13 \cdot 5 \pm 1 \cdot 5$	10·0135	As	$-8 \cdot 8 \pm 1 \cdot 5$	74·934
B^{11}	$10 \cdot 0 \pm 1 \cdot 5$	11·0110	Kr^{78}	$-9 \cdot 4 \pm 2$	77·926
C	$3 \cdot 0 \pm 1$	12·0036	Br^{79}	$-9 \cdot 0 \pm 1 \cdot 5$	78·929
N	$5 \cdot 7 \pm 2$	14·008	Kr^{80}	$-9 \cdot 1 \pm 2$	79·926
O	$0 \cdot 0$	16·0000	Kr^{81}	$-8 \cdot 6 \pm 1 \cdot 5$	80·926
F	$0 \cdot 0 \pm 1$	19·0000	Kr^{82}	$-8 \cdot 8 \pm 1 \cdot 5$	81·927
Ne^{20}	$0 \cdot 2 \pm 1$	20·0004	Kr^{83}	$-8 \cdot 7 \pm 1 \cdot 5$	82·927
Ne^{22}	(2·2 ?	22·0048)	Kr^{84}	$-8 \cdot 5 \pm 1 \cdot 5$	83·928
P	$-5 \cdot 6 \pm 1 \cdot 5$	30·9825	Kr^{86}	$-8 \cdot 2 \pm 1 \cdot 5$	85·929
			I	$-5 \cdot 3 \pm 2$	126·932
Tin (eleven isotopes)	....	....	Sn^{120}	$-7 \cdot 3 \pm 2$	119·912
Xenon (nine isotopes)	....	....	Xe^{134}	$-5 \cdot 3 \pm 2$	133·929
Mercury (six isotopes)	....	....	Hg^{200}	$+0 \cdot 8 \pm 2$	200·016

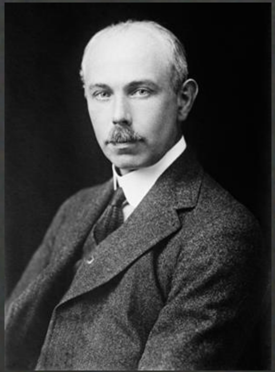
1927



Francis William Aston

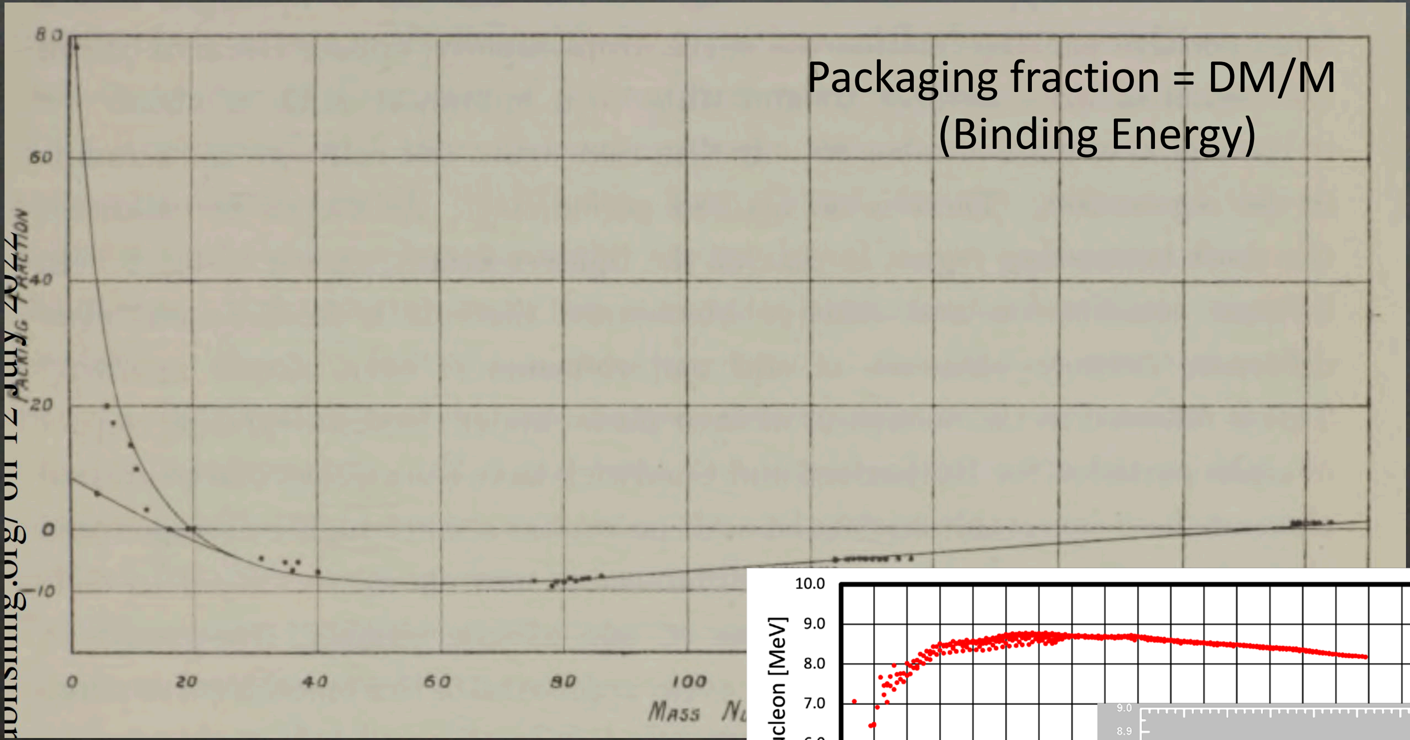


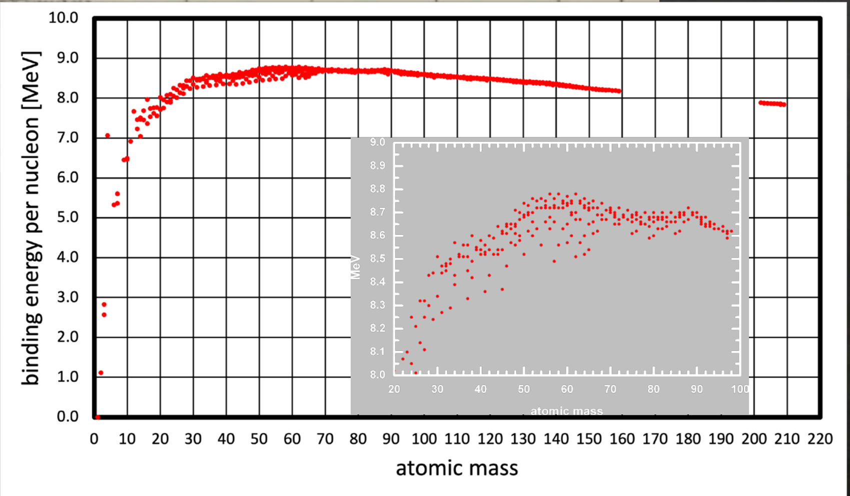
1927



Francis William Aston

Packaging fraction = DM/M
(Binding Energy)





1868 -> 1927

Dmitrij Ivanovič Mendeleev

groups the 63 elements known at that time based on their chemical properties and ranks them in order of atomic mass

Antonius Johannes van den Broek

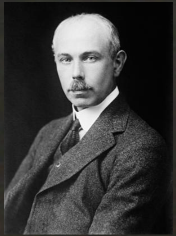
Intra nucleus charge (Z) roughly half the atomic mass (A)? The position of an element in the Mendeleev table corresponds to its intra nucleus charge Z? Unfortunately this is certainly not true for the heaviest elements.

Henry Moseley

Frederick Soddy

Demonstrate that the elements in the Mendeleev table are ranked in term of Z and not A (both Moseley and Soddy). “Substances” of different mass may occupy the same position in the Mendeleev table and are therefore named ISOTOPES (Soddy). First chart of the nuclides (A versus Z) (Soddy)

Francis William Aston



Finds the first isotopes (^{20}Ne and ^{22}Ne) and states that only H does not have a whole mass number (A=1.008). In 1927 finds a quiet large number if isotopes and shows that no atomic mass is a whole number. He plots for the first time the mass defect, that he calls "packaging factor”, that we now call Binding Energy

1916

William Draper Harkins

THE ABUNDANCE OF THE ELEMENTS IN RELATION TO THE HYDROGEN-HELIUM STRUCTURE OF THE ATOMS

By William D. Harkins

KENT CHEMICAL LABORATORY, UNIVERSITY OF CHICAGO

Received by the Academy, February 26, 1916

According to the theory already presented in a number of papers[1] the atoms of all the 91 elements of our ordinary system heavier than hydrogen are built up as intra-atomic (not chemical) compounds of hydrogen. The first of these 91 elements, helium, is the second in the system, and therefore has the atomic number 2. It has an atomic weight of 4.00, and may be considered to be composed of 4 hydrogen atoms. The element of atomic number 3, lithium, has an atomic weight of about 7. Now it has been found that in general among the elements of low atomic weight, the elements of even atomic number, beginning with helium, seem to be built up from helium atoms, and

1916

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A preliminary study of the most recent analyses of meteorites of different classes showed that, either for any one class or for the meteorites as a whole *the even numbered or helium system elements are very much more abundant than those of the odd numbered or lithium system.* For a more detailed study use was made of the data collected by Farrington,[5] who suggests that the average composition of meteorites may represent the composition of the earth as a whole.

The results obtained by averaging the analyses of 318 iron and 125 stone meteorites, 443 in all, show that the first seven elements in order of abundance are iron, nickel, silicon, magnesium, sulphur, and calcium;

Harkins' rule

1925

Cecilia Helena Payne
(Gaposchkin)

HARVARD OBSERVATORY MONOGRAPHS

HARLOW SHAPLEY, EDITOR

No. 1

STELLAR ATMOSPHERES

A CONTRIBUTION TO THE OBSERVATIONAL STUDY OF HIGH TEMPERATURE IN THE REVERSING LAYERS OF STARS

BY

CECILIA H. PAYNE

1925 – PhD thesis(25 yrs old)

1925

Cecilia Helena Payne
(Gaposchkin)

TABLE XXVIII

Atomic Number	Atom	Log a_r	Atomic Number	Atom	Log a_r	Atomic Number	Atom	Log a_r
1	H	11	13	Al	5.0	23	V	3.0
2	He	8.3	14	Si	4.8	24	Cr	3.9
	He+	12		Si+	4.9	25	Mn	4.6
3	Li	0.0		Si+++	6.0	26	Fe	4.8
6	C+	4.5	19	K	3.5	30	Zn	4.2
11	Na	5.2	20	Ca	4.8	38	Sr	1.8
12	Mg	5.6		Ca+	5.0		Sr+	1.5
	Mg+	5.5	22	Ti	4.1	54	Ba+	1.1

The most obvious conclusion that can be drawn from Table XXVIII is that all the commoner elements found terrestrially, which could also, for spectroscopic reasons, be looked for in the stellar atmosphere, are actually observed in the stars. The twenty-four elements that are commonest in the crust of the earth,[13] in order of atomic abundance, are oxygen, silicon, hydrogen, aluminum, sodium, calcium, iron, magnesium, potassium, titanium, carbon, chlorine, phosphorus, sulphur, nitrogen, manganese, fluorine, chromium, vanadium, lithium, barium, zirconium, nickel, and strontium.

The most abundant elements found in stellar atmospheres, also in order of abundance, are silicon, sodium, magnesium, aluminum, carbon, calcium, iron, zinc, titanium, manganese, chromium, potassium, vanadium, strontium, barium, (hydrogen, and helium). All the atoms for which quantitative estimates have been made are included in this list. Although hydrogen and helium are manifestly very abundant in stellar atmospheres, the actual values derived from the estimates of marginal appearance are regarded as spurious.

Henry Russell (director of the Observatory of the Princeton University) heavily criticized the H and He abundances calculated by Cecilia Payne.

1929

Henry Norris Russell

Contributions from the Mount Wilson Observatory, No. 383
Reprinted from the *Astrophysical Journal*, Vol. LXX, pp. 11–82, 1929
Printed in the U.S.A.

ON THE COMPOSITION OF THE SUN'S ATMOSPHERE

By HENRY NORRIS RUSSELL[1]

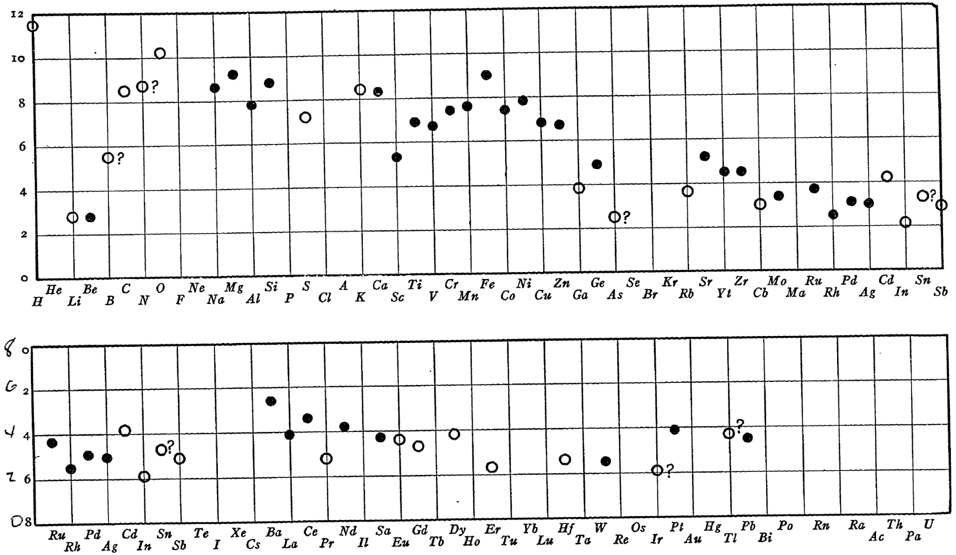

FIG. 3.—Values of log Q, where Q represents the total mass of the atoms or molecules of an element per unit area of the sun's surface.

Hydrogen must be extremely abundant in the atmosphere of the red giants, for its lines are stronger in their spectra than in that of the sun. With any reasonable allowance for the effect of the lower

So…..

at the end of the 20's it was known that the number of nuclei to be understood (explained) is much higher than the number of chemical species, that the abundances of the even species (alpha nuclei) is much larger than that of the odd ones (Li nuclei) and that H and He are extremely abundant in the Sun (i.e. the chemical composition of the Earth is not representative of the one of the stars)

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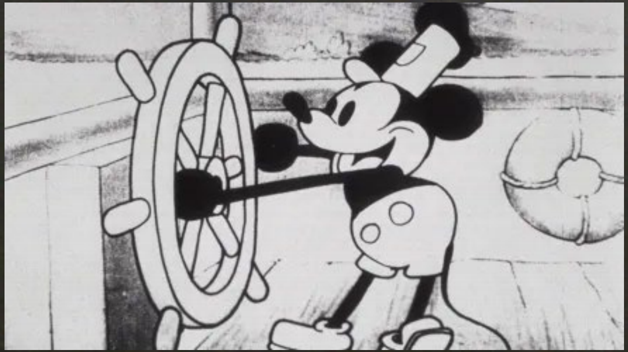
1928, November 18 the first Mickey Mouse short movie is released (Steamboat Willie)



So.....

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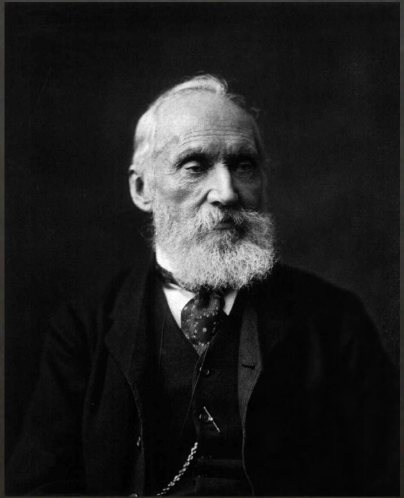
But ..... which is the connection with the stars?

Hermann Ludwig Ferdinand von Helmholtz

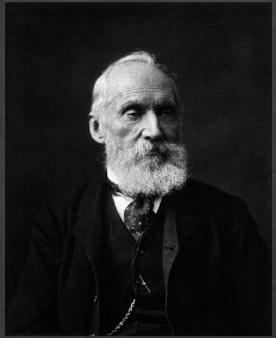
He was the first to propose the gravitational contraction as the energy source of the Sun



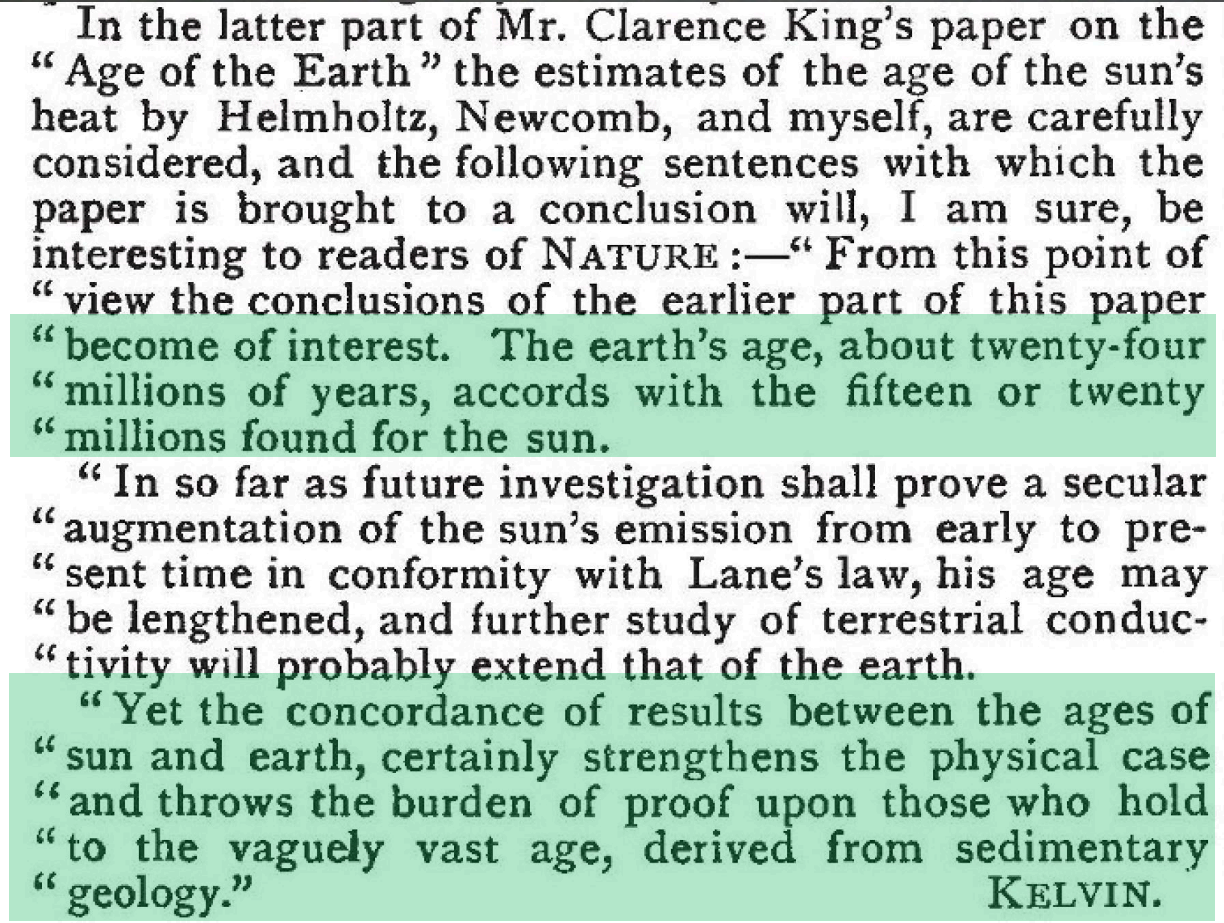
William Thomson, 1st Baron Kelvin

He was the noun and the staunchest supporter of the von Helmhotz idea

1895



William Thomson
1st Baron Kelvin

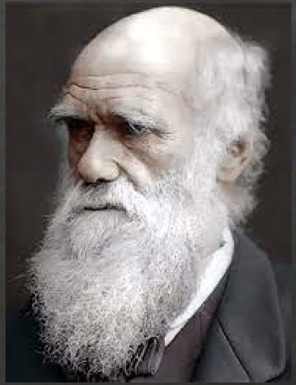


In the latter part of Mr. Clarence King's paper on the "Age of the Earth" the estimates of the age of the sun's heat by Helmholtz, Newcomb, and myself, are carefully considered, and the following sentences with which the paper is brought to a conclusion will, I am sure, be interesting to readers of NATURE:—"From this point of "view the conclusions of the earlier part of this paper "become of interest. The earth's age, about twenty-four "millions of years, accords with the fifteen or twenty "millions found for the sun.

"In so far as future investigation shall prove a secular "augmentation of the sun's emission from early to pre- "sent time in conformity with Lane's law, his age may "be lengthened, and further study of terrestrial conduc- "tivity will probably extend that of the earth.

"Yet the concordance of results between the ages of "sun and earth, certainly strengthens the physical case "and throws the burden of proof upon those who hold "to the vaguely vast age, derived from sedimentary "geology." KELVIN.

The whole community of geologists rose up against the William Thompson determination of the age of the Earth



Charles Robert Darwin

1859 The study of the erosion of the rocks on the Weild Valley showed that these rocks are roughly 300 Myr old

Baltwood

1907 The datation of the rocks via the U decay led to an age of the order of 300/400 Myr

1907

Ernest Rutherford

THE JOURNAL
OF THE
ROYAL ASTRONOMICAL SOCIETY
OF CANADA

VOL. I. MAY-JUNE, 1907. No. 3.

SOME COSMICAL ASPECTS OF RADIOACTIVITY.

BY E. RUTHERFORD.

Lord Kelvin attacked this question of the age of the earth by supposing that the earth was originally at a temperature of molten rock and has since that time gradually been cooling by the radiation of heat through the surface into space. According to this theory, the temperature gradient near the surface of the earth has been gradually decreasing. Knowing the temperature gradient to-day, and the average conductivity and specific heat of the materials of the earth, it is possible by the aid of Fourier's celebrated analysis to deduce the interval that has elapsed since the earth was a molten mass. Some of the values of the quantities necessary in the calculation are uncertain within limits, but Lord Kelvin concluded that certainly not more than 100 million years can have elapsed since the surface of the earth was at a temperature capable of supporting animal and vegetable life. In later papers this estimate has been still further reduced, and the age of the earth is put as low as forty million years. I cannot here enter into the intermittent controversy that has raged for nearly half a century between Lord Kelvin on the one hand and the geologists and biologists on the other. The latter initially required a much longer period for the progress of geologic and biologic evolution than that allowed by Kelvin, but there appears to be a general consensus of opinion among geologists and biologists to-day, that a period of 100 million years allows sufficient time for the processes of evolution.

I hope that I have made clear to you how the study of radioactivity has profoundly altered our views of the earth's internal heat. The conclusions advanced are by no means completely proved, but sufficient has been done to cast grave doubt on the validity of the older theories of the origin and variation of the earth's internal heat.

probably much less. There is one possibility, however, which may greatly extend the estimate of the duration of the sun's heat. At the enormous temperature of the sun, it is possible that ordinary matter may become radioactive, *i.e.*, it may break up into simpler forms, with the evolution of a great quantity of heat. If ordinary matter, in undergoing such change, emitted as much heat as radium in its transformation, this new source of heat would allow the sun to shine for a much longer period than the older theory allows. This is only a speculation, but

Radioactivity may increase significantly both the age of the Earth an of the Sun.

1919

Henry Norris Russell

PUBLICATIONS
OF THE
Astronomical Society of the Pacific.

Vol. XXXI. San Francisco, California, July, 1919 No. 182

ON THE SOURCES OF STELLAR ENERGY[1]

By Henry Norris Russell

2. It must therefore be assumed that there exists within the stars some unknown store of energy of enormous magnitude, which is made available to supply the heat lost by radiation. Tho the nature of the process by which this energy is transformed is unknown, we do know that it must satisfy certain conditions:

(*a*) It must generate large quantities of heat per unit mass in the interior of the stars, and very little or none under laboratory conditions, or in the interior of the Earth.

(*b*) It must not be liable to accelerate its own rate so as to end in an explosive catastrophe, for the stars in general appear to be very stable, and the phenomena of Novae are apparently superficial rather than deep-seated.

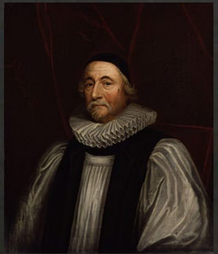
(*c*) It must in some way be regulated so as to supply heat to each star at almost exactly the rate at which the star radiates heat to space, for the rate of energy transformation in the processes of stellar evolution is evidently exceedingly slow.

(*d*) It must ultimately die down as time goes on, making it possible for a star to proceed to the dwarf stages in which its radiation is small.

(*e*) A sufficient amount of energy must still be available in these later stages to permit them to be of very long duration, for the large majority of the stars per unit of volume are dwarfs.

1920

Sir Arthur Stanley Eddington



Archbishop Usher

famous because he scientifically computed the age of the world since its creation (based on the Bible)

The Internal Constitution of the Stars.*

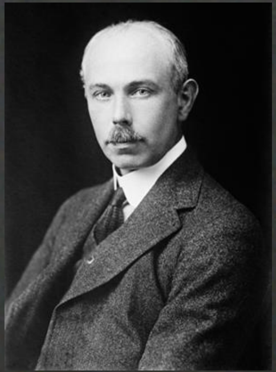
By PROF. A. S. EDDINGTON, M.A., M.Sc., F.R.S.

consequences. Lord Kelvin showed that this hypothesis, due to Helmholtz, necessarily dates the birth of the sun about 20,000,000 years ago; and he made strenuous efforts to induce geologists and biologists to accommodate their demands to this time-scale. I do

If the contraction theory were proposed to-day as a novel hypothesis I do not think it would stand the smallest chance of acceptance. From all sides—bio-

theory would be held to be negatived definitely. Only the inertia of tradition keeps the contraction hypothesis alive—or, rather, not alive, but an unburied corpse.

1919/1920



Francis William Aston

Remember that….

November

Neon.

IN response to inquiries, may I use your columns to make two announcements in reference to the above?

First, by making use of a new and more powerful method of positive-ray analysis (the description of which is now in the press), I have succeeded in obtaining measurements of mass and other evidence of sufficient accuracy to prove beyond all dispute that atmospheric neon (atomic weight 20·200, O=16) is a mixture of two isotopes of atomic weights 20·00 and 22·00 correct to about 1/10th per cent.

Secondly, permission to publish being now granted, a full account of recent experiments on "Neon Lamps for Stroboscopic Work" will shortly appear in the Proceedings of the Cambridge Philosophical Society.

F. W. ASTON.

Cavendish Laboratory, Cambridge,
November 19.

July 1920

By far the most important result obtained from this work is the generalisation that, with the exception of hydrogen, all the atomic weights of all elements so far measured are exactly whole numbers on the scale O=16 to the accuracy of experiment (1 in 1000). By means of a special

method (see *Phil. Mag.*, May, 1920, p. 621), some results of which are given in spectrum vii., hydrogen is found to be 1·008, which agrees with the value accepted by chemists. This exception from the whole number rule is not unexpected, as on the Rutherford "nucleus" theory the hydrogen atom is the only one not containing any negative electricity in its nucleus.

1920

Sir Arthur Stanley Eddington

The Internal Constitution of the Stars.*

By PROF. A. S. EDDINGTON, M.A., M.Sc., F.R.S.

the chemists agree with him. There is a loss of mass in the synthesis amounting to about 1 part in 120, the atomic weight of hydrogen being 1·008 and that of helium just 4. I will not dwell on his beautiful proof

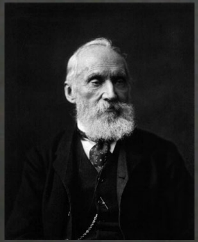
when helium is made out of hydrogen. If 5 per cent. of a star's mass consists initially of hydrogen atoms, which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy.

isotope of helium from them; and what is possible in the Cavendish Laboratory may not be too difficult in the sun. I think that the suspicion has been gener-

seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race—or for its suicide.

Where the Sun luminosity comes from?

1895

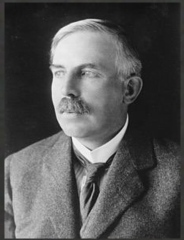


Hermann von Helmholtz

W. Thompson (Lord Kelvin)

Gravitational contraction

1907



Ernest Rutherford

radioactivity

1919

Henry Norris Russell

rejects the idea of the gravitational contraction and makes a list of constraints that the unknown energy source must satisfy

1920

Sir Arthur Eddington

suggests the mass defect between H and He as the energy source because M(H)=1.008 and M(He)=4. All elements could be produced by "accretion" of successive H nuclei.

Eddington's idea that the solar energy source could be the result of the fusion of four atoms of H in one of He run in two insurmountable problems:

1) the fusion of $4p+2e^- \rightarrow {}^4He$ requires an interaction among ***SIX*** bodies: very, very unlikely!

2) the energy required to overcome the Coulomb barrier is of the order of the MeV, occurrence which would require a temperature in excess of several GK. (Eddington already demonstrated (1918) that the central temperature of the Sun is no more than few 10 MK)

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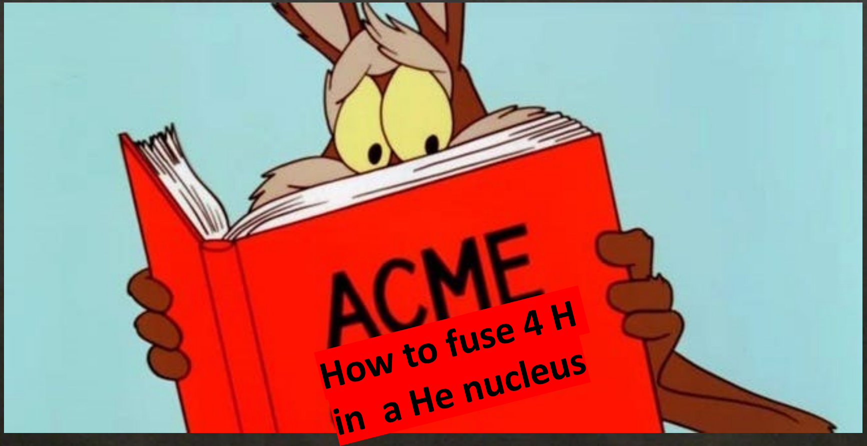

1928

Georgij Antonovič Gamov

The Quantum Theory of Nuclear Disintegration.

In a very interesting letter published in NATURE of Sept. 22, p. 439, Gurney and Condon have used wave mechanics to give a qualitative explanation of many features of natural α-ray disintegration. It may be of interest to point out that using very similar assumptions, it is possible to give a quantitative explanation of these features and also to throw light on the phenomenon of artificial disintegration. I should therefore be glad to be permitted to give a short account of these investigations here.

In the model of the nucleus adopted (G. Gamow, *Zs. f. Phys.*, Bd. 51, p. 204) the region of the inverse square law forces extends inwards, without serious perturbations, to a critical distance r_0 which is appreciably less than the closest distance of approach of the α-particles, calculated on classical mechanics, for which inverse square law scattering at large angles is still observed. For distances less than r_0 there exist attractive forces which vary very quickly with the distance. An α-particle of suitable energy can stay inside the nucleus for long periods of time, periods which on the classical theory would be infinite, since the α-particle could never pass over the potential barrier. On the wave picture, on the other hand, no such barrier can ever completely prevent a gradual leaking out of the waves, representing the process of escape of α-particles.

1928

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..... but he does not apply the same formalism to the fusion of two particles.....

attractive forces which vary very quickly with the distance. An α-particle of suitable energy can stay inside the nucleus for long periods of time, periods which on the classical theory would be infinite, since the α-particle could never pass over the potential barrier. On the wave picture, on the other hand, no such barrier can ever completely prevent a gradual leaking out of the waves, representing the process of escape of α-particles.

1931

Robert d'Escourt Atkinson

ATOMIC SYNTHESIS AND STELLAR ENERGY. I

BY R. D'E. ATKINSON

He was the first to propose that elements may be synthesized by means of successive proton (and electron) captures.

Granted the helium then, it is not difficult to suppose that many or all other known elements (and perhaps many unstable ones unknown to us in addition) might be formed by cumulative syntheses. But if unstable elements are formed (and we know that some exist), a source of helium is provided; the process becomes completely self-supplying. In fact, if the temperature and density are suitable for syntheses in general, a rapidly increasing amount of synthesis will actually start as soon as even one other atom (stable or unstable) is present in the hydrogen. For if synthesis can build this up to a point of instability, it will presumably build up the resulting helium nucleus to the same point, and so on; each nucleus, once it reaches this point, will be able to emit α-particles—and not simply once but indefinitely. The nucleus acts as a sort of trap and cooking-pot[3] combined, catching four protons and two electrons in such sequence and at such intervals as may prove practicable, fettering them by emitting as radiation most of the surplus mass brought in

Aufbauhypothese

Starting from He all nuclei are obtained by capture of single proton (and electrons every now and then)

The capture of four protons may push matter out of the stability valley, the successive decay would provide an alpha particle and the original nucleus. A neverending cycle.

The father of the CNO cycle!

The idea that the various elements were formed by means of the

aufbauhypothese

was readily accepted by the community but...how to realize it in practice?

Harold Clayton Urey

1931 He discovers the deuterium

James Chadwick

February 1932: Letter to Nature to communicate the discovery of the neutron

1937-1938

Carl Friedrich Freiherr von Weizsäcker

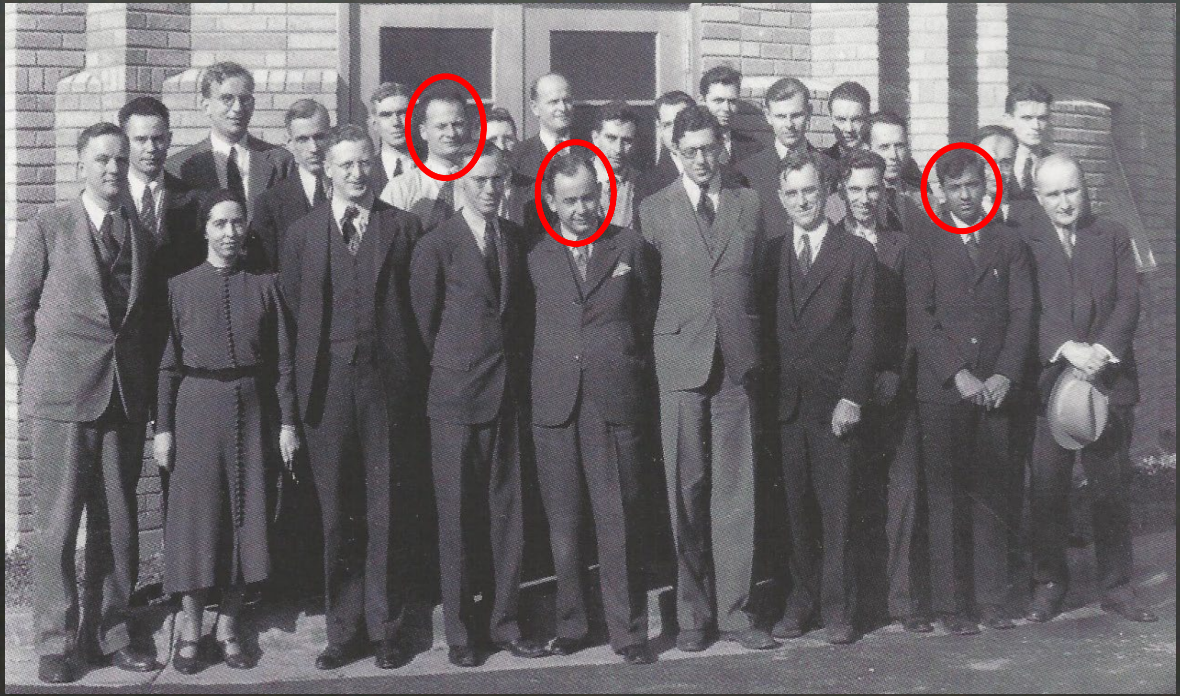
The problems of energy generation and transmutation of the elements in the interior of the stars has recently been investigated by von Weizsäcker.[1] Through a discussion of the processes between light atomic nuclei the conclusion is reached that the net result of these is the transmutation of hydrogen into helium and neutrons. The neutrons are immediately captured by heavier atomic nuclei. Formation of heavier elements is due almost exclusively to such neutron capture processes.

Stromgren 1938 (ApJ 87,520)

Modifies the original idea of Atkinson introducing the idea that the elements may be produced by successive neutron captures

$$^{4}He + P \to {}^{5}Li \to {}^{5}He + P \to {}^{4}He + {}^{2}H$$

$$^{2}H + {}^{2}H \to {}^{3}He + n$$



George Washington University: The 4th conference in 1938 on Stellar Energy and Nuclear Processes.

Astrophysicists (Chandrasekhar, Menzel, Sterne, and Strömgren) met nuclear physicists (Bethe, Breit, Gamow, Hafstad, Neumann, Teller, and Tuve) to discuss the problem of the energy production and nucleosynthesis in stars.

Carl Friedrich Freiherr von Weizsäcker

also

1938 Suggests a PRESTELLAR origin for the elements (NSE)

(Physik. Zeits. 39, 633)

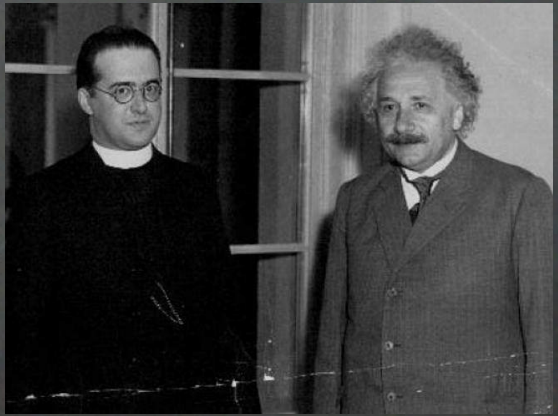
(mentioned by Gamow in 1947 - PhysRevL 70, 572)

1927

A Homogeneous Universe of Constant Mass and Increasing Radius accounting for the Radial Velocity of Extra-galactic Nebulæ. By Abbé G. Lemaître.

(*Translated by permission from "Annales de la Société scientifique de Bruxelles," Tome XLVII, série A, première partie.*)

The receding velocities of extragalactic nebulæ are a cosmical effect of the expansion of the universe. The initial radius R_0



Georges Lemaitre and Albert Einstein

1929

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

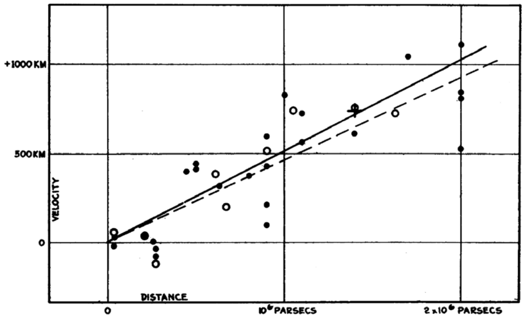


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of

Edwin Hubble

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of

1938 May

The Problem of Stellar Energy

Subrahmanyan Chandrasekhar

George Gamov

Merle A. Tuve

The lack of stable nuclei with A=5,8 does not allow the synthesis of the elements starting from He

They suggest that the energy necessary to replace the energy losses from the surface of the Sun can be provided by the:

$$^1H + ^1H \rightarrow ^2H + \beta^+$$

On the fundamental problem concerning the nuclear transformations as the source of energy of stars, some interesting conclusions have been reached. According to the so-called "aufbauhypothese", the process of the building up of the heavier elements from hydrogen is continually taking place in stellar interiors. Further, it is assumed that such processes liberate sufficient amounts of energy to account for the radiation of the stars. However, it seems that the model scheme proposed by von Weizsäcker ($^4_2He + ^1_1H \rightarrow ^5_3Li \rightarrow ^5_2He + \beta+$) is contradicted by recent experimental evidence, according to which the nuclei ^5_3Li and ^5_2He are both unstable, emitting heavy particles in a very short time. Another possible chain of reactions for the synthesis of the heavier elements from hydrogen and helium would require the stability of ^8_4Be, which is again very doubtful according to recent experimental evidence. It appears, then, that the only course not excluded by present evidence on the binding energies of the light nuclei is the formation of ^6_4Be in triple collisions involving an α-particle and two protons.

Although the existence of ^6_4Be has not yet been established experimentally, there are some indications that it might be a stable nucleus. If so, the chain of reactions leading to the synthesis of the heavier nuclei from hydrogen can be traced. The estimate of the probability of such reactions involving triple collisions shows that, under the conditions in the stellar interiors, the rate of liberation of energy will be sufficient to account for the radiation of the stars.

As another possibility the reaction $^1_1H + ^1_1H \rightarrow ^2_1H + \beta+$ was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective sources of energy are required.

1938 May

The Problem of Stellar Energy

Subrahmanyan Chandrasekhar

George Gamov

Merle A. Tuve

The lack of stable nuclei with A=5,8 does not allow th

The quest of the solar energy source is decoupled from the synthesis of the elements

They suggest that the energy necessary to replace the energy losses from the surface of the Sun can be provided by the:

$$^{1}\mathrm{H} + ^{1}\mathrm{H} \rightarrow ^{2}\mathrm{H} + \beta^{+}$$

On the fundamental problem concerning the nuclear transformations as the source of energy of stars, some interesting conclusions have been reached. According to the so-called "aufbauhypothese", the process of the building up of the heavier elements from hydrogen is continually taking place in stellar interiors. Further, it is assumed that such processes liberate sufficient amounts of energy to account for the radiation of the stars. However, it seems that the model scheme proposed by von Weizsäcker ($^{4}_{2}\mathrm{He} + ^{1}_{1}\mathrm{H} \rightarrow ^{5}_{3}\mathrm{Li} \rightarrow ^{5}_{2}\mathrm{He} + \beta+$) is contradicted by recent experimental evidence, according to which the nuclei $^{5}_{3}\mathrm{Li}$ and $^{5}_{2}\mathrm{He}$ are both unstable, emitting heavy particles in a very short time. Another possible chain of reactions for the synthesis of the heavier elements from hydrogen and helium would require the stability of $^{8}_{4}\mathrm{Be}$, which is again very doubtful according to recent experimental evidence. It appears, then, that the only course not excluded by present evidence on the binding energies of the light nuclei is the forma-

particle

t been established experimentally, there are some indications that it might be a stable nucleus. If so, the chain of reactions leading to the synthesis of the heavier nuclei from hydrogen can be traced. The estimate of the probability of such reactions involving triple collisions shows that, under the conditions in the stellar interiors, the rate of liberation of energy will be sufficient to account for the radiation of the stars.

As another possibility the reaction $^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{1}\mathrm{H} + \beta+$ was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective sources of energy are required.

1938 June

Hans Albrecht Bethe

Charles Louis Critchfield

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

The Formation of Deuterons by Proton Combination

H. A. Bethe, *Cornell University, Ithaca, N. Y.*

AND

C. L. Critchfield, *George Washington University, Washington, D. C.*

(Received June 23, 1938)

The probability of the astrophysically important reaction $H+H=D+\epsilon^+$ is calculated. For the probability of positron emission, Fermi's theory is used. The penetration of the protons through their mutual potential barrier, and the transition probability to the deuteron state, can be calculated exactly, using the known interaction between two protons. The energy evolution due to the reaction is about 2 ergs per gram per second under the conditions prevailing at the center of the sun (density 80, hydrogen content 35 percent by weight, temperature $2\cdot10^7$ degrees). This is almost but not quite sufficient to explain the observed average energy evolution of the sun (2 ergs/g sec.) because only a small part of the sun has high temperature and density. The reaction rate depends on the temperature approximately as $T^{3.5}$ for temperatures around $2\cdot10^7$ degrees.

In calculating the energy evolution from reaction (1), it must be considered that (1) is followed by a number of other reactions which are all "fast" in comparison with (1) because they involve the emission of radiation or of heavy particles rather than of β-rays.[3] The deuterons formed in reaction (1) will first capture another proton, with γ-ray emission:

$$D+H=He^3+\gamma. \qquad (2)$$

If He^3 is more stable:

$$\begin{aligned} He^3+He^4&=Be^7+\gamma,\\ Be^7&=Li^7+\epsilon^+,\\ Li^7+H&=2He^4. \end{aligned} \qquad (3)$$

They do not mention at all the $^3He+^3He$

1938 September

Hans Albrecht Bethe

Energy Production in Stars

In several recent papers,[1–3] the present author has been quoted for investigations on the nuclear reactions responsible for the energy production in stars. As the publication of this work which was carried out last spring has been unduly delayed, it seems worth while to publish a short account of the principal results.

December 1938

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

Published March 1939

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

assumption of a N^{14} concentration of 10 percent by weight, this gives an energy evolution of

$$\frac{6\cdot 10^{23}\cdot 0.1}{14}\cdot 3\cdot 10^{-20}\approx 100 \text{ ergs/g sec.} \qquad (45)$$

at "standard stellar conditions," i.e., $T=2\cdot 10^7$, $\rho=80$, hydrogen concentration 35 percent.

1938 September

Hans Albrecht Bethe

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1938 September

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Energy Production in Stars

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December 1938

Direct formation of C^{12}

C^{12} may be formed directly in a collision between 3 α-particles. The calculation of the probability is exactly the same as for the formation of B^9. The nonresonance process gives about the same probability as a resonance of Be^8 at 50 kev. With $\rho=80$, $x_\alpha=\frac{1}{4}$, $\Gamma=0.1$ electron-volt, $T=2\cdot10^7$ degrees, the probability is 10^{-56} per α-particle, i.e., about 10^{-37} of the proton combination reaction (1). This gives an even smaller yield of C^{12} than the chains described in this and the preceding section. The process is strongly temperature-dependent, but it requires temperatures of $\sim10^9$ degrees to make it as probable as the proton combination (1).

The considerations of the last two sections show that there is no way in which nuclei heavier than helium can be produced permanently in the interior of stars under present conditions. We can therefore drop the discussion of the building up of elements entirely and can confine ourselves to the energy production which is, in fact, the only observable process in stars.

seminal ideas:

1) elements synthesized by neutron captures in stars
2) prestellar origin of the elements

1938: fantastic year!

H+H -> D may produce enough energy to account for the Sun's luminosity

compute the nuclear cross section of the H+H -> D

1) identify the CN cycle to power the luminosity of the stars more massive than the Sun and confirms the PP chain for stars less massive than the Sun
2) Computes the nuclear cross section of the 3α and concludes that at 20 MK can not work because temperatures in excess of 1GK would be necessary.
3) **Hence, he concludes that it is NOT possible to synthesize nuclear species beyond He in the stars.**

1939 October

George Gamow

NUCLEAR REACTIONS IN STELLAR EVOLUTION*

By Prof. G. Gamow,

George Washington University, Washington, D.C.

Summing up, we can say that, due to the application of our present knowledge of nuclear physics, the problem of stellar energy sources and the main features of stellar evolution can be considered at present as practically solved.

1939 October

George Gamow

NUCLEAR REACTIONS IN STELLAR EVOLUTION*

By Prof. G. Gamow,
George Washington University, Washington, D.C.

1937, December 21 the "Snow White and the seven dwarfs" was released

applicat… nuclear
physics, … ces and
the mai… be con-
sidered a…

1942

Subrahmanyan Chandrasekhar

A prestellar origin of the elements begins to be explored

NSE: T of several GK and density r of millions of gr/cm^3

$$y_{i(Z,N)} = f(A, T, \rho) y_p^z y_n^n e^{-\frac{Q(z,n)}{kT}}$$

AN ATTEMPT TO INTERPRET THE RELATIVE ABUNDANCES OF THE ELEMENTS AND THEIR ISOTOPES

S. CHANDRASEKHAR AND LOUIS R. HENRICH

ABSTRACT

In this paper an attempt is made to derive some information concerning the prestellar stage at which the elements are supposed to have been formed. By using first the relative abundances of the isotopes of a single element (e.g., *O*, *Ne*, *Mg*, *Si*, and *S*), it is shown that a temperature of the order of a few billion degrees is indicated. The equilibrium between the fundamental nuclear particles (protons, neutrons, α-particles, electrons, and positrons) at temperatures ranging from 5 to 10 billion degrees is then studied to establish the relative concentrations of protons and neutrons as a function of the temperature. This relation is then used to compute theoretical mass-abundance-curves under different physical conditions. From such calculations it is concluded that under the physical conditions specified by $T = 8 \times 10^9$ degrees and $\rho = 10^7$ gm/cm^3 the theoretical mass-abundance-curve from oxygen to sulphur agrees fairly satisfactorily with the known abundance-curve according to V. M. Goldschmidt (Fig. 2). An important feature of the nuclear mixture considered is that hydrogen and helium are the two most abundant constituents, which is in agreement with known facts. However, the conditions indicated are seen to be quite insufficient to account for the existence of the heavy nuclei to any appreciable extent. It is, therefore, suggested that we should distinguish at least two epochs in the development of the prestellar stage. We imagine that at the earliest stages conditions of extreme temperatures and densities prevailed at which the heavier nuclei could have been formed. As the matter cooled to lower temperatures and densities, appreciable amounts (1 part in 10^6) of the heavy elements must have been "frozen" into the mixture. At temperatures of the order of from 5×10^9 to 8×10^9 degrees and densities of the order of from 10^4 to 10^7 gm/cm^3 the present known relative abundances of the elements from oxygen to sulphur may have been established.

1. *Introduction.*—It is now generally agreed that the chemical elements cannot be synthesized under conditions now believed to exist in stellar interiors. Consequently, the question of the origin of the elements is left open. On the other hand, the striking regularities which the relative abundances of the elements and their isotopes reveal (e.g., Harkins' rule) require some explanation. It has therefore been suggested that the

1942

Subrahmanyan Chandrasekhar

A prestellar origin of the elements begins to be explored

NSE: T of several GK and density r of millions of gr/cm³

$$y_{i(Z,N)} = f(A, T, \rho) y_p^z y_n^n e^{-\frac{Q(z,n)}{kT}}$$

AN ATTEMPT TO INTERPRET THE RELATIVE ABUNDANCES OF THE ELEMENTS AND THEIR ISOTOPES

S. Chandrasekhar and Louis R. Henrich

For an assigned temperature the neutron concentration was so adjusted that the relative concentration of the nuclei ${}^{16}_{8}O$ and ${}^{36}_{18}A$ occurring in the equilibrium mixture was approximately the same as that known to occur in the "cosmos"—according to Goldschmidt, approximately in the ratio 15,000:1. After having adjusted the physical conditions in this manner, the complete theoretical mass-abundance-curve was computed according to equation (20) and the table of atomic masses given by Barkas.

Calculations of the kind outlined in the preceding paragraph have been made for different initially assigned temperatures, and the results are summarized in Table 3.

In Figure 2 we have compared the theoretical abundances of the elements beyond oxygen, according to Table 3, with the abundances given by Goldschmidt.[9] An examination of this figure shows that the better agreement with the computed and the observed abundances is obtained under the conditions:

$$\left.\begin{aligned} T &= 8 \times 10^9 \text{ degrees} , \\ \log n_p &= 29.83 , \\ \log n_\nu &= 29.30 , \\ \log n_2^4 &= 30.3 , \end{aligned}\right\} \qquad (22)$$

or

$$\rho = 10^7 \text{ gm/cm}^3 ; \qquad T = 8 \times 10^9 \text{ degrees} . \qquad (23)$$

1942

Subrahmanyan Chandrasekhar

A prestellar origin of the elements begins to be explored

NSE: T of several GK and density r of millions of gr/cm^3

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AN ATTEMPT TO INTERPRET THE RELATIVE ABUNDANCES OF THE ELEMENTS AND THEIR ISOTOPES

S. CHANDRASEKHAR AND LOUIS R. HENRICH

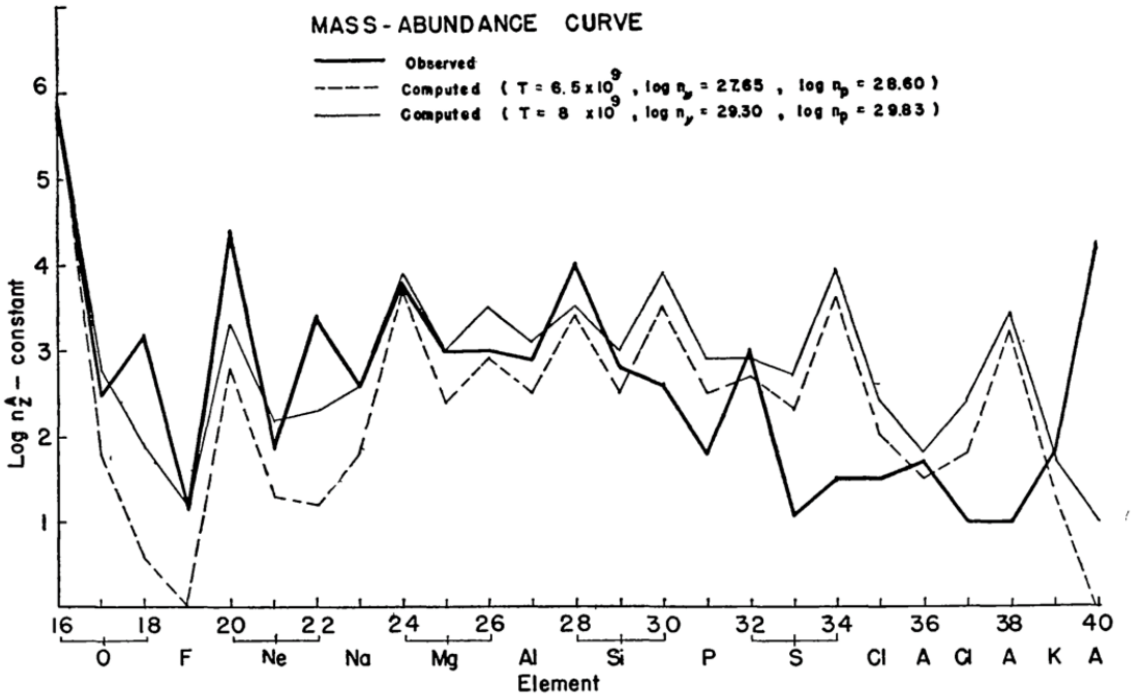


FIG. 2

1946

George Gamow

Expanding Universe and the Origin of Elements

G. Gamow
The George Washington University, Washington, D. C.
September 13, 1946

It is generally agreed at present that the relative abundances of various chemical elements were determined by physical conditions existing in the universe during the early stages of its expansion, when the temperature and density were sufficiently high to secure appreciable reaction-rates for the light as well as for the heavy nuclei.

In all the so-far published attempts in this direction the observed abundance-curve is supposed to represent some equilibrium state determined by nuclear binding energies at some very high temperature and density.[1–3] This point of view encounters, however, serious difficulties in the comparison with empirical facts. Indeed, since binding energy is, in a first approximation, a linear function of atomic weight, any such equilibrium theory would necessarily lead to a rapid exponential decrease of abundance through the entire natural sequence of elements. It is known, however, that whereas such a rapid decrease actually takes place for the first half of chemical elements, the abundance of heavier nuclei remains nearly constant.[4] Attempts have been made[2] to explain this discrepancy by the assumption that heavy elements were formed at higher temperatures, and that their abundances were already "frozen" when the adjustment of lighter elements was taking place. Such an explanation, however, can be easily ruled out if one remembers that at the temperatures and densities in question (about 10^{10}°K, and 10^6 g/cm^3) nuclear transformations are mostly caused by the processes of absorption and re-evaporation of free neutrons so that their rates are essentially the same for the light and for the heavy elements. Thus it appears that the only way of explaining the observed abundance-curve lies in the assumption of some kind of unequilibrium process taking place during a limited interval of time.

The abundances of the various elements cannot be explained by an NSE

means that *at the epoch when the mean density of the universe was of the order of 10^6 g/cm^3, the expansion must have been proceeding at such a high rate, that this high density was reduced by an order of magnitude in only about one second.*

Returning to our problem of the formation of elements, we see that *the conditions necessary for rapid nuclear reactions were existing only for a very short time*, so that it may be quite dangerous to speak about an equilibrium-state which must have been established during this period.

Coagulation of neutrons in larger and larger complexes

It is also interesting to notice that the calculated time-period during which rapid nuclear transformations could have taken place is considerably shorter than the β-decay period of free neutrons which is presumably of the order of magnitude of one hour. Thus if free neutrons were present in large quantities in the beginning of the expansion, the mean density and temperature of expanding matter must have dropped to comparatively low values *before* these neutrons had time to turn into protons. We can anticipate that neutrons forming this comparatively cold cloud were gradually coagulating into larger and larger neutral complexes which later turned into various atomic species by subsequent processes of β-emission.

1946

Sir Fred Hoyle

THE SYNTHESIS OF THE ELEMENTS FROM HYDROGEN *

F. Hoyle

(Received 1946 April 6 †)

The elements DO form inside the stars but again at the NSE

Summary

Stars that have exhausted their supply of hydrogen in regions where thermonuclear reactions are important enter a collapsing phase. If the mass of the star exceeds Chandrasekhar's limit collapse will continue until rotational instability occurs. Rotational instability enables the star to throw material off to infinity. This process continues until the mass of the remaining stellar nucleus becomes of the order of, or less than Chandrasekhar's limit. The nucleus can then attain a white dwarf equilibrium state.

The temperature generated at the centre of a collapsing star is considered and it is shown that values sufficiently high for statistical equilibrium to exist between the elements must occur. The relative abundances of the elements can then be worked out from the equations of statistical mechanics. These equations are considered in detail and it is shown that a roughly uniform abundance of the elements over the whole of the periodic table can be obtained. The process of rotational instability enables the heavy elements built up in collapsing stars to be distributed in interstellar space.

The results arising from the discussion of the formation of heavy elements lead to a natural explanation of the difference between novae and supernovae.

1948

Ralph Asher Alpher

Hans Albrecht Bethe

George Gamow

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. Bethe
Cornell University, Ithaca, New York

AND

G. Gamow
The George Washington University, Washington, D. C.

February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It

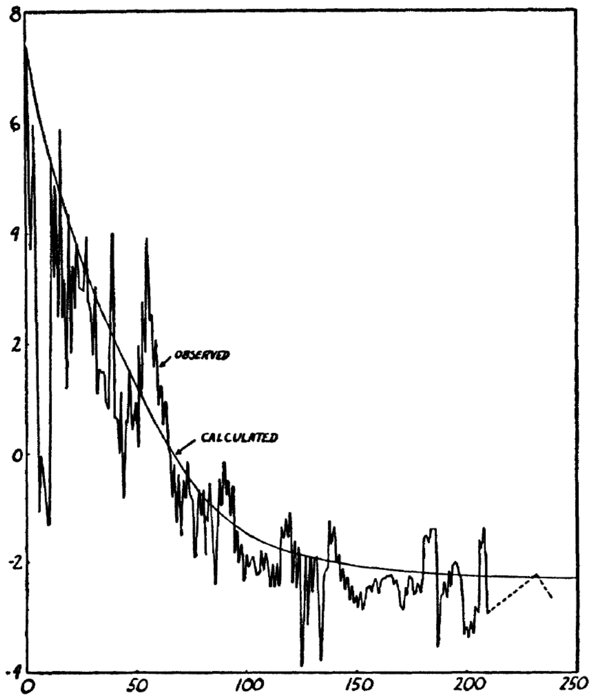
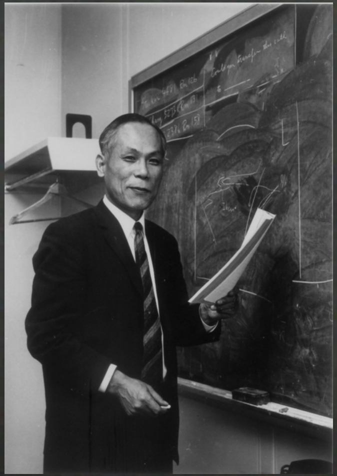


Fig. 1.

Log of relative abundance

Atomic weight

1950



Chūshirō Hayashi

Proton-Neutron Concentration Ratio in the Expanding Universe at the Stages preceding the Formation of the Elements.

Chushiro HAYASHI.

Department of Physics, Naniwa University.

(Received January 12, 1950)

In the universe in which $\rho_r > \rho_m$ and at high temperatures where elements are not allowed to be in existence, the n-p ratio follows the curves shown in Fig. 2. It can be seen in particular that, if the existing laws of physics, microscopic and macroscopic, are valid at least up to temperatures $\sim 2\times 10^{10}$°K, the n-p ratio at the beginning of the elements formation, i. e., at $x \gtrsim 1$, is nearly 1 : 4, whatever the physical conditions at higher temperatures, especially at the epoch $t=0$ when the universe is singular according to the current theory, may be.

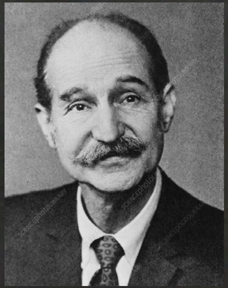
It is known that at present hydrogen and helium together form about 97 percent of all matter. If we assume that formation of nuclei heavier than He^4 can be neglected, and that reactions involving beta-processes such as $n \to p + e^-$, $p + p \to H^2 + e^+$, and $H^3 \to He^3 + e^-$, which are much slower than other nuclear transmutations such as gamma-ray or particle emission unless material density is extremely low, are not effective during the formation process, He^4 is built up from original neutrons and protons, after all, as $2n + 2p \to He^4$, whatever the routes of formation may be, for instance $n + p \to H^2$, $H^2 + H^2 \to H^3 + p$, $H^3 + H^2 \to He^4 + n$, or $n + p \to H^2$, $H^2 + n \to H^3$, $H^3 + p \to He^4$. Consequently, the hydrogen-helium abundance ratio (in number) resulting from the initial n-p ratio 1 : 4 becomes 6 : 1, whereas recent observed values in stellar atmospheres and meteorites range from 5 : 1 to 10 : 1.

Under the original assumption of Gamow that "ylem" consists solely of neutrons, it is difficult to explain the fact that the building-up processes of the elements jump over the "crevasses" of unstable mass numbers 5 and 8, as shown by Fermi and Turkevitch.[5] However, the existence of an appreciable amount of

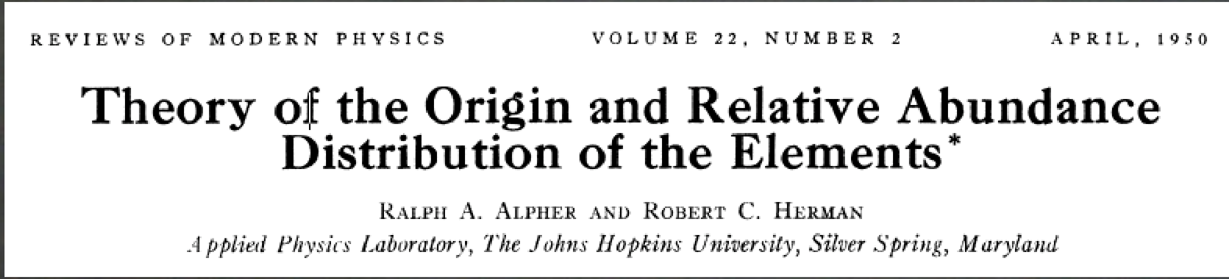
February 7, 1940 – the movie Pinocchio is released

1950

Ralph Asher Alpher



Robert Herman



REVIEWS OF MODERN PHYSICS VOLUME 22, NUMBER 2 APRIL, 1950

Theory of the Origin and Relative Abundance Distribution of the Elements*

RALPH A. ALPHER AND ROBERT C. HERMAN

Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

Two categories of models proposed to explain the origin of the elements (both prestellar):

Equilibrium (Chandrashekhar, Henrich): single or double NSE

Non equilibrium (Gamow, Alpher): expansion too fast to reach the NSE.
Elements form as drops of neutrons part of which later decay in protons

Additional scenario(Sir Fred Hoyle): NSE in stars

1950

Robert Noel Hall

William Alfred Fowler

PHYSICAL REVIEW VOLUME 77, NUMBER 2 JANUARY 15, 1950

The Cross Section for the Radiative Capture of Protons by C^{12} near 100 Kev

Robert Noel Hall and William Alfred Fowler
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received September 15, 1949)

A low voltage accelerator and high current ion source has been used to determine the cross section of the reaction $C^{12}(p\gamma)N^{13}$ over the energy range from 88 to 128 kev. A counter arrangement is described which detects 26 percent of all the positrons from the decay of the N^{13} produced in the reaction and which has a low background rate of 5.5 counts per minute. With this accelerator and detector, yields of the order of 10^{-16} positron per proton and cross sections as low as 10^{-10} barn or 10^{-34} cm^2 can be measured with errors of the order of ± 20 percent. The cross section for the $C^{12}(p\gamma)N^{13}$ reaction has been found to fit the semi-empirical expression $\sigma = 0.0024E^{-1}\exp[-6E^{-\frac{1}{2}}]$ barn with E in Mev over the energy range measured. This is in satisfactory agreement with the Breit-Wigner one-level dispersion formula using constants determined at the 456-kev resonance. The astrophysical implications of these results in connection with the carbon-nitrogen cycle of nuclear reactions in stellar interiors are discussed.

INTRODUCTION

In 1938 H. A. Bethe[1] showed that the most important source of energy in ordinary stars is the nuclear reactions of carbon and nitrogen with protons. These reactions which form a cycle in which the original nucleus is reproduced are as follows:

$$\begin{aligned} &C^{12}+H^1\rightarrow N^{13}+\gamma, && N^{13}\rightarrow C^{13}+\beta^+ +\nu,\\ &C^{13}+H^1\rightarrow N^{14}+\gamma, && \\ &N^{14}+H^1\rightarrow O^{15}+\gamma, && O^{15}\rightarrow N^{15}+\beta^+ +\nu.\\ &N^{15}+H^1\rightarrow C^{12}+He^4 && \end{aligned} \quad (1)$$

above is the only one consistent with the known evolution of energy in the bright stars of the main sequence, including the sun, and with the central temperature of these stars as calculated by integration of the Eddington equations ($\sim 2\times 10^7$ degrees). For fainter stars with lower central temperatures the reaction

$$H^1+H^1\rightarrow D^2+\beta^+ +\nu, \quad (2)$$

and the reactions following it were suggested[2] as being mainly responsible for the energy production.

The essential point of Bethe's argument cannot be

1953

Edwin Ernest Salpeter

ANNUAL REVIEWS Further

Quick links to online content

ENERGY PRODUCTION IN STARS[1]

By E. E. Salpeter

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

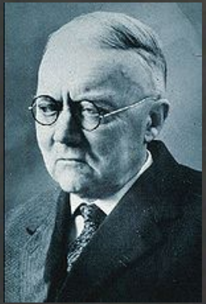
in a few million years. At this stage of its contraction its central density is about 2×10^4 gm./cc. and its central temperature T_c about 2×10^8 °K. Although, for ordinary main sequence stars, reactions involving triple collisions are quite unimportant, at these high densities and temperatures the exothermic conversion of three He^4 nuclei into one C^{12} nucleus becomes frequent enough to be able to supply the energy radiated away by the star [Öpik (27); Salpeter (28)].

The reaction proceeds in two steps

$$\left.\begin{aligned} He^4 + He^4 + 95\ \text{kev} &\rightarrow Be^8 + \gamma \\ He^4 + Be^8 &\rightarrow C^{12} + \gamma + 7.4\ \text{Mev} \end{aligned}\right\} \qquad 8.$$

The nucleus Be^8 is unstable to disintegration into two He^4 nuclei. But the energy required for its formation from two helium nuclei is only (95 ± 5) kev which is not very much larger than the mean thermal energies at temperatures over 10^8 °K. Thus a small fraction (about 1 in 10^{10}) of the material in the interior of the star is constantly in the form of Be^8 in a state of dynamic equilibrium. The Be^8 present then easily undergoes a (α, γ) reaction and over 7 Mev per C^{12} nucleus is liberated in the form of radiation.[7]

1954 (1951)



Ernst Opik

6 — THE CHEMICAL COMPOSITION OF WHITE DWARFS

BY

E. J. ÖPIK

Armagh Observatory, N. Ireland

It has been pointed out by the writer [1] that, after the complete exhaustion of hydrogen, but before the final collapse into the white dwarf stage, the internal temperature of stars with masses exceeding 0.5—0.7 $\odot$ may rise high enough for the conversion of all, or most of its helium into heavier elements. The reaction made responsible for this process would consist in triple collisions of helium nuclei leading to the formation of one carbon nucleus, according to

$$\left.\begin{aligned} He^4 + He^4 &\rightarrow (Be^8), && (a) \\ (Be^8) + He^4 &\rightarrow C^{12} + \gamma\ . && (b) \end{aligned}\right\} \quad (1)$$

Reaction (1)(a) would correspond to penetration only, not necessarily followed by the formation of true Be^8. The frequency of the reaction is thus assumed proportional to the encounter cross-section (square of the de Broglie wave-length), and to the probability of penetration (non-resonance case), without the probability factor for radiative capture. The life-time of the temporary nucleus (Be^8) formed is assumed equal to $\sim 8 \times 10^{-21}$ sec, being an estimate of the duration of penetration. The life-time of true Be^8 is probably much shorter, about 10^{-22} sec [(7), *et alias*].

The frequency of the reaction (1)(b) can be calculated with the usual formulae, e.g. those of Gamow or Bethe. Non-resonance capture is assumed in this case also.

Defining the life-time of helium through

$$t_o = -Y \Big/ \left(\frac{dY}{dt}\right), \qquad (2)$$

where Y = concentration of helium by weight, from Gamow's formulae [(8), allowance being made for several errata, only partly pointed out by the author] it is found as follows [(1), p. 71] :

$$t_o = 1.5 \times 10^{-12}\, Y^{-2} \rho^{-2}\, T^{4/3}\, e^{\,37100/T^{1/3}} \text{ (seconds)}. \qquad (3)$$

The formula has been checked and should represent well the order of magnitude for the non-resonance processes. Here ρ = density g/cm³, T = temperature °K. The reaction is astrophysically significant for $T > 3 \times 10^8$, and very intense at $T > 4 \times 10^8$ (1).

The formation of C^{12} from helium has been considered also by E.E. Salpeter (2), apparently without a knowledge of the writer's previous suggestion. His method of calculation is not quite clear from his brief note. It seems that reaction (1)(a) he has treated in a manner similar to ours, whereas in (1)(b) he has postulated a resonance process. The outcome is a formula yielding 1.4×10^{13} times higher an energy generation with a practically similar temperature dependence as that of equation (3). Of the discrepancy, a factor of 10^3 - 10^4 seems to refer to reaction (a) and is about equivalent to the omission of the probability of penetration; the rest, a factor of $10^9 — 10^{10}$, is about what might be expected for the difference in the rate of a resonance reaction (with low-lying resonance levels), and that of a non-resonance process at $T = 2 \times 10^8$.

1953

D.N.F. Dunbar

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

The 7.68-Mev State in C^{12}

D. N. F. Dunbar,* R. E. Pixley, W. A. Wenzel, and W. Whaling
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(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68±0.03 Mev. At $E_d=620$ kev, $\theta_{\rm lab}=90°$, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

Salpeter[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of $O^{16}:C^{12}:He^4$ that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C^{12}.

An early measurement of the range of the alpha particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} at 7.62 Mev.[4] However, a recent magnetic analysis of this reaction failed to detect a transition to any level in this region of excitation,[5] nor did the level show up in the neutron spectrum[6] from $B^{11}(d,n)C^{12}$. From the

* On leave from the University of Melbourne, Melbourne, Australia.

1 E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.

2 E. J. Öpic, Proc. Roy. Irish Acad. **A54**, 49 (1952).

3 F. Hoyle (private communication).

4 M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

5 R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).

6 W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 586 (1949); V. R. Johnson, Phys. Rev. **86**, 302 (1952).

1954

Sir Fred Hoyle

$3\alpha \rightarrow {}^{12}\mathrm{C}$

${}^{12}\mathrm{C}(\alpha,\gamma){}^{16}\mathrm{O}$

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. Hoyle*

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

Received December 22, 1953

The present paper aims to show that the abundances of the chemical elements over the portion of the periodic table from carbon to nickel are consistent with the view that the elements originate at the high temperatures that probably occur in the interiors of certain types of star. The argument takes its

It was pointed out some years ago by Bethe (1939) that effective element-building inside stars must proceed, in the absence of hydrogen, by triple α-particle collisions as a starting point:

$$3\alpha \rightarrow C^{12} + \gamma. \tag{24}$$

It is convenient to replace reaction (24) by

$$\alpha + \alpha \rightleftarrows Be^8, \qquad Be^8 + \alpha \rightarrow C^{12} + \gamma. \tag{27}$$

This is a permissible step, since the lifetime of the unstable Be^8 is appreciably longer than the time required for a "nuclear" collision of two α-particles; that is, longer than the

$A_0 = 4$, $Z_0 = 2$, and $A_1 = 8$, $Z_1 = 4$, in the formulae of the previous section. The important energy level of the C^{12} nucleus in the present problem is one very recently identified by Dunbar, Pixley, Wenzel, and Whaling (1953). This level occurs at about 7.68 mev above ground level, which corresponds to a value of E_R of about 0.31 mev. (It will

It can be shown that reaction (25) is the most effective in destroying C^{12}. Hence, to decide how far C^{12} accumulates, it is necessary to compare the rates of reactions (24) and (25). For the latter reaction the value of E_R of main interest is -0.05 mev, corresponding

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ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE*

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CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953

$$\frac{dn_2^4}{dt} = -3A\,(n_2^4)^3 - Bn_2^4 n_6^{12},$$

$$\kappa = \frac{2.2 \times 10^{-24} B}{A\,\rho}.$$

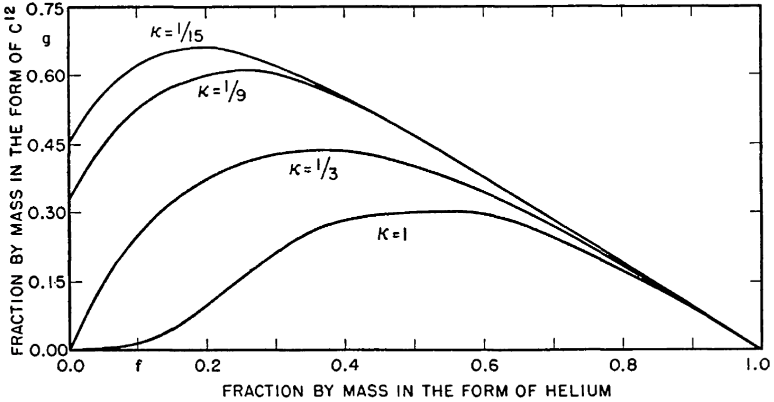

FIG. 2.—The formation of C^{12} from helium as a function of κ. The quantity f represents the fraction of the mass which is helium; g is the fraction which is C^{12}; the balance, $1-f-g$, is O^{16}.

The ratio of the mass of O^{16} produced to the mass of C^{12} produced may be estimated as

$$\left(\frac{1-g}{g}\right)_{f=0}. \qquad \frac{^{12}\mathrm{C}}{^{16}\mathrm{O}} \sim 0.5 \tag{37}$$

To agree with observed cosmic abundances, this ratio should take a value of about $\frac{2}{1}$, which would imply a value of κ not much greater than $\frac{1}{9}$. It is, however, to be emphasized

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ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

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So far we have considered the nuclear reactions occurring in the temperature range around 0.14 as if the material were initially entirely pure helium. It is, of course, the case that the material must initially contain traces of other elements. From the present point of view the important trace elements are C^{13} and N^{14}.

presence of N^{14} leads to the reactions

$$N^{14} + \alpha \rightarrow F^{18} + \gamma \,, \tag{46}$$

$$F^{18} \rightarrow O^{18} + \beta^{+} \,, \tag{47}$$

$$O^{18} + \alpha \rightarrow Ne^{22} + \gamma \,, \tag{48}$$

The presence of the trace element C^{13} likewise leads to the reactions

$$C^{13} + \alpha \rightarrow O^{17} + \gamma \,, \tag{49}$$

$$O^{17} + \alpha \rightarrow Ne^{21} + \gamma \,. \tag{50}$$

It remains to be added that F^{19} is produced by the reaction

$$N^{15} + \alpha \rightarrow F^{19} + \gamma \,. \tag{51}$$

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Sir Fred Hoyle

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

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Received December 22, 1953

ABUNDANCE RATIOS RELATIVE TO Fe^{56} (LOGARITHMS TO BASE 10)

	NUCLEUS											
	Ti^{48}	Cr^{52}	Fe^{54}	Mn^{55}	Fe^{57}	Fe^{58}	Ni^{58}	Co^{59}	Ni^{60}	Ni^{62}	Cu^{63}	Zn^{64}
Theoretical abundances.........	−3.3	−0.38	−0.47	−2.3	−2.3	−2.0	−1.5	−2.6	−0.67	−3.1	−4.8	−5.0
Meteoritic abundances.........	−2.6	−1.9	−1.2	−2.0	−1.6	−2.5	−1.8	−2.4	−1.4	−2.7	−3.4	−3.9
Adopted binding energy per nucleon (mev) (only differences affect the calculated abundances)........	+8.702	+8.773	+8.737	+8.764	+8.769	+8.793	+8.733	+8.768	+8.785	+8.782	+8.741	+8.725

He does not discuss neither the neutron source(s) nor the synthesis of the nuclei beyond the Fe peak

1955

William Alfred Fowler

Geoffrey Ronald Burbidge

Eleanor Margaret Burbidge

STELLAR EVOLUTION AND THE SYNTHESIS OF THE ELEMENTS

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Cavendish Laboratory, University of Cambridge

AND

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Cambridge

Received March 7, 1955; revised April 7, 1955

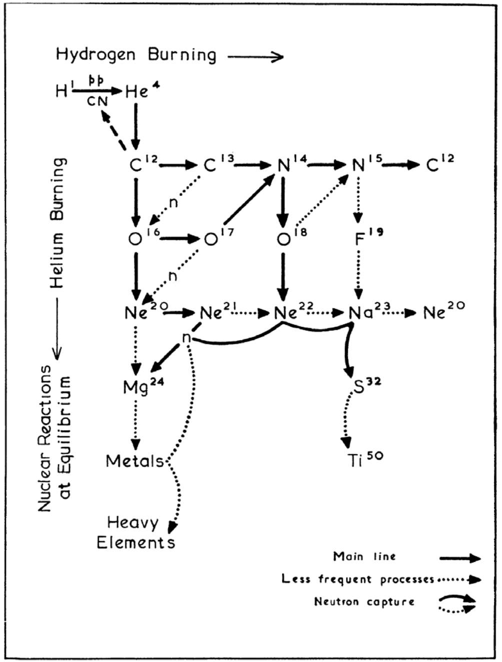
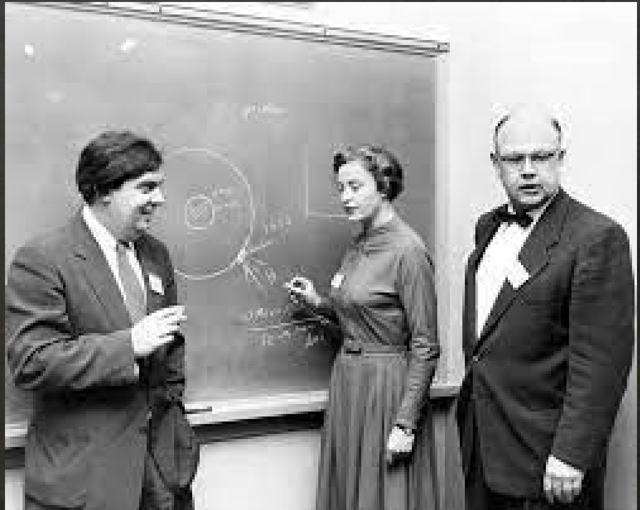


Fig. 2 —This figure shows schematically the basic processes involved in the synthesis of the elements. These are (i) hydrogen-burning, (ii) helium-burning, (iii) nuclear reactions at equilibrium at $\sim 5 \times 10^{9\circ}$, and (iv) neutron capture.



1956

Hans Eduard Suess

Harold Clayton Urey

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 1 JANUARY, 1956

Abundances of the Elements*

HANS E. SUESS,† *U. S. Geological Survey, Washington, D. C.*

AND

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*

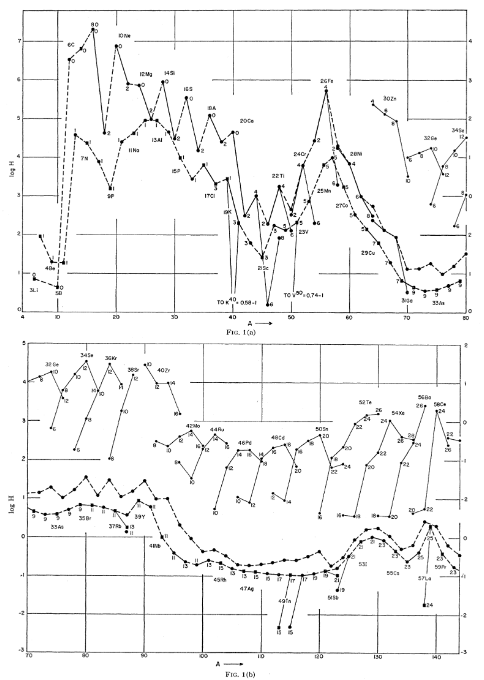


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FIG. 1(a)

FIG. 1(b)

FIGS. 1(a)–1(c). Logarithm of abundance (silicon = 6) plotted against mass number (A). The even and odd mass numbers are on separate curves. The neutron excess numbers (I) are shown at each point. The curve without I indicated, shows the sum of the isobaric abundances for the even A series. Note that the right-hand scale is for the curve representing the even A series (light lines) beginning with $A=64$ (Zn). [Part (c) on opposite page.]

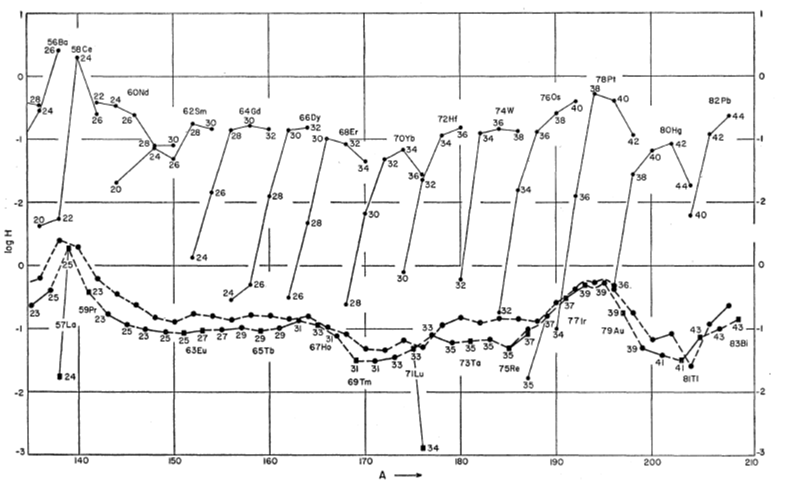

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FIG. 1(c). (Caption on opposite page.)

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5 October 1956, Volume 124, Number 3223 SCIENCE

Origin of the Elements in Stars

F. Hoyle, William A. Fowler,
G. R. Burbidge, E. M. Burbidge

Experimental (*1, 1a*) and observational (*2–6*) evidence has continued to accumulate in recent years in support of the theory (*7–10*) that the elements have been and are still being synthesized in stars. Since the appearance of a new and remarkable analysis by Suess and Urey (*11*) of the abundances of the elements, we have found it possible to explain, in a general way, the abundances of practically all the isotopes of the elements from hydrogen through uranium by synthesis in stars and supernovae. In this article we wish to outline in a qualitative fashion the essentially separate mechanisms which are required in stellar synthesis (*12*).

thesis would not be possible. In theories of primordial synthesis, the break in the neutron-capture chain at He^4 has been an insuperable stumbling block. In contrast, it is the saving factor in stellar neutron synthesis. We emphasize that there

At temperatures from about 10^7 to 5×10^7 degrees in main-sequence stars, hydrogen is transformed to helium, $4H^1 \rightarrow He^4$, with an average binding energy of 7.07 million electron volts (Mev) per nucleon. We emphasize that the proton-proton sequence of reactions makes possible the production of helium starting only with hydrogen. The recent discovery of the free neutrino as reported by Cowan *et al.* (*1a*) leads to increased confidence in the existence of the primary proton-proton interaction which proceeds through prompt electron-neutrino emission. At temperatures from 10^8 to 2×10^8 degrees in red giant stars, He^4 is transformed principally to C^{12}, O^{16}, and Ne^{20} with an average binding energy of 7.98 Mev per nucleon. The important roles of the ground state of Be^8 and of the second excited state of C^{12} in expediting the primary process of helium fusion, $3He^4 \rightarrow C^{12}$, have recently been clarified (*1*), and it is now clear that the long-standing difficulties in element synthesis at mass 5 and mass 8 are bypassed in this process. At temperatures of the order 10^9 degrees, Mg^{24}, Si^{28}, S^{32}, A^{36}, and Ca^{40} are formed from the carbon, oxygen, and neon, the average binding thus rising to 8.55 Mev per nucleon, while, at temperatures from 2×10^9 to 5×10^9 degrees, Fe^{56} and neighboring nuclei are synthesized, yielding an average binding energy of 8.79 Mev per nucleon. No higher binding than this exists,

The situation, then, is that a thermal "cooking" of pure hydrogen yields principally He^4 and the α-particle nuclei with $A = 4n$, $Z = 2n$, $n = 3, 4, 5, 6, 7, 8, 9$, and 10 (C^{12} to Ca^{40}), together with nuclei centered around Fe^{56}. These are the most abundant nuclei. Moreover, the relative

During the $H \rightarrow He^4$ stage of second-generation stars, Ne^{20} is processed by the reactions $Ne^{20}(p,\gamma)Na^{21}$, $Na^{21}(\beta^+)Ne^{21}$. During the latter stage of the phase, $He^4 \rightarrow C^{12}$, O^{16}, Ne^{20}, free neutrons are generated by $Ne^{21}(\alpha,n)Mg^{24}$. The free neutrons are partly added to the light elements with $A = 4n$, producing the remaining isotopes of these elements, and are partly added to Fe^{56} and allied nuclei. Because the Fe^{56} is present in only very low abundance, the number of neu-

We have distinguished two conditions under which the neutron capture can take place, a slow (*s*) process and a rapid (*r*) process. Suess and Urey (*11*) and Coryell (*13*) have already pointed out that the peaks in the abundance curves at stable nuclei with filled neutron shells ($A = 90, N = 50$; $A = 139, N = 82$; $A = 208$, $N = 126$) strongly indicate the operation of the *s*-process in element synthesis and that the nearby peaks at $A = 82$, 130, and 194, shifted by $\delta A \sim 8$ to 14, similarly require the operation of the *r*-process. The *s*-process we associate with giant stars that evolve in approximately 10^5 years. We regard the observed presence (*2*) of technetium in the atmospheres of the giant S-type stars as a demonstration that the building of very heavy elements by neutron addition actually takes place in stars. The *r*-process we associate with the explosion of supernovae, the time scale being as small as 10 to 100 seconds. We regard the

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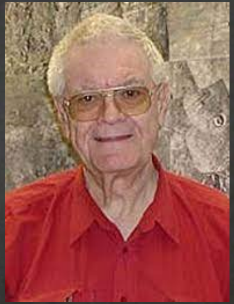

Alastair G. W. Cameron

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 69 June 1957 No. 408

NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

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Chalk River, Ontario

TABLE I

Mechanisms of Nucleogenesis

Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors
	2. Neutron capture on slow time scale
	3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements:	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae
	2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

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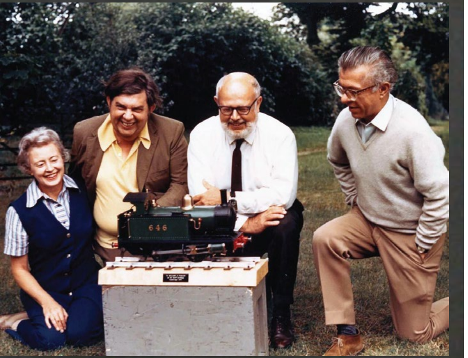

REVIEWS OF

MODERN PHYSICS

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Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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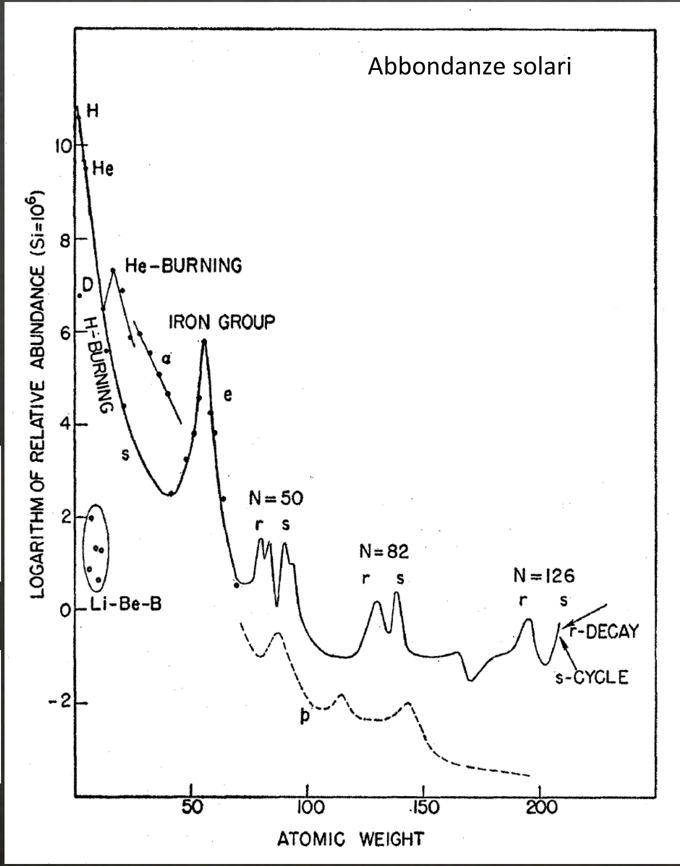
1957

Stellar scenario

to conclude as follows. The basic reason why a theory of stellar origin appears to offer a promising method of synthesizing the elements is that the changing structure of stars during their evolution offers a succession of conditions under which many different types of nuclear processes can occur. Thus the internal

Pre stellar scenario

are characteristic of the rise to explosion. On the other hand, the theory of primeval synthesis demands that all the varying conditions occur in the first few minutes, and it appears highly improbable that it can reproduce the abundances of those isotopes which are built on a long time-scale in a stellar synthesis theory.



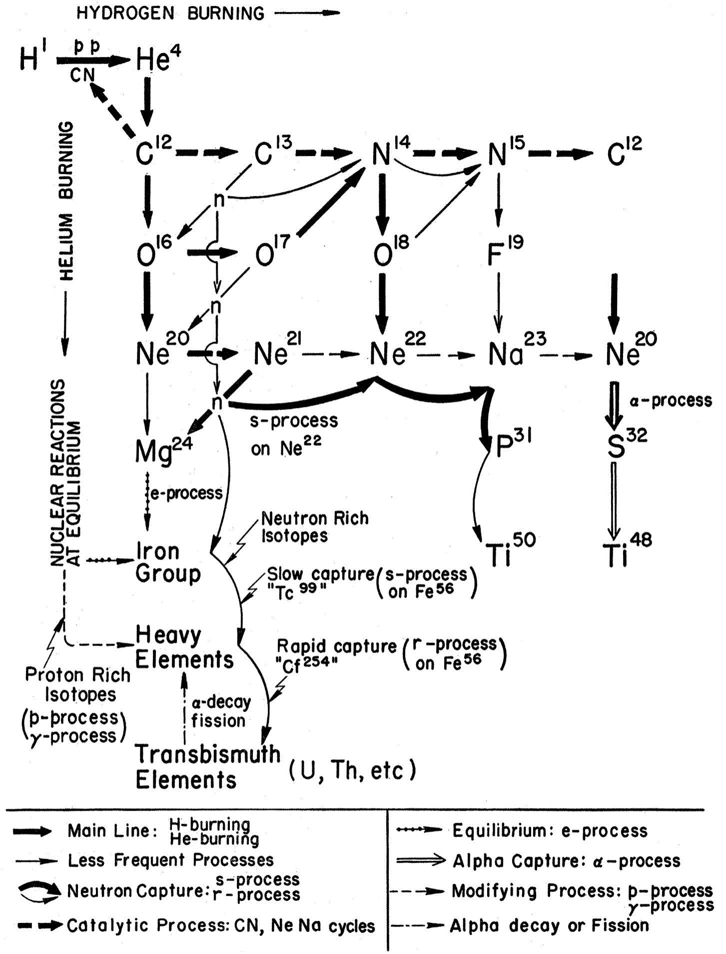
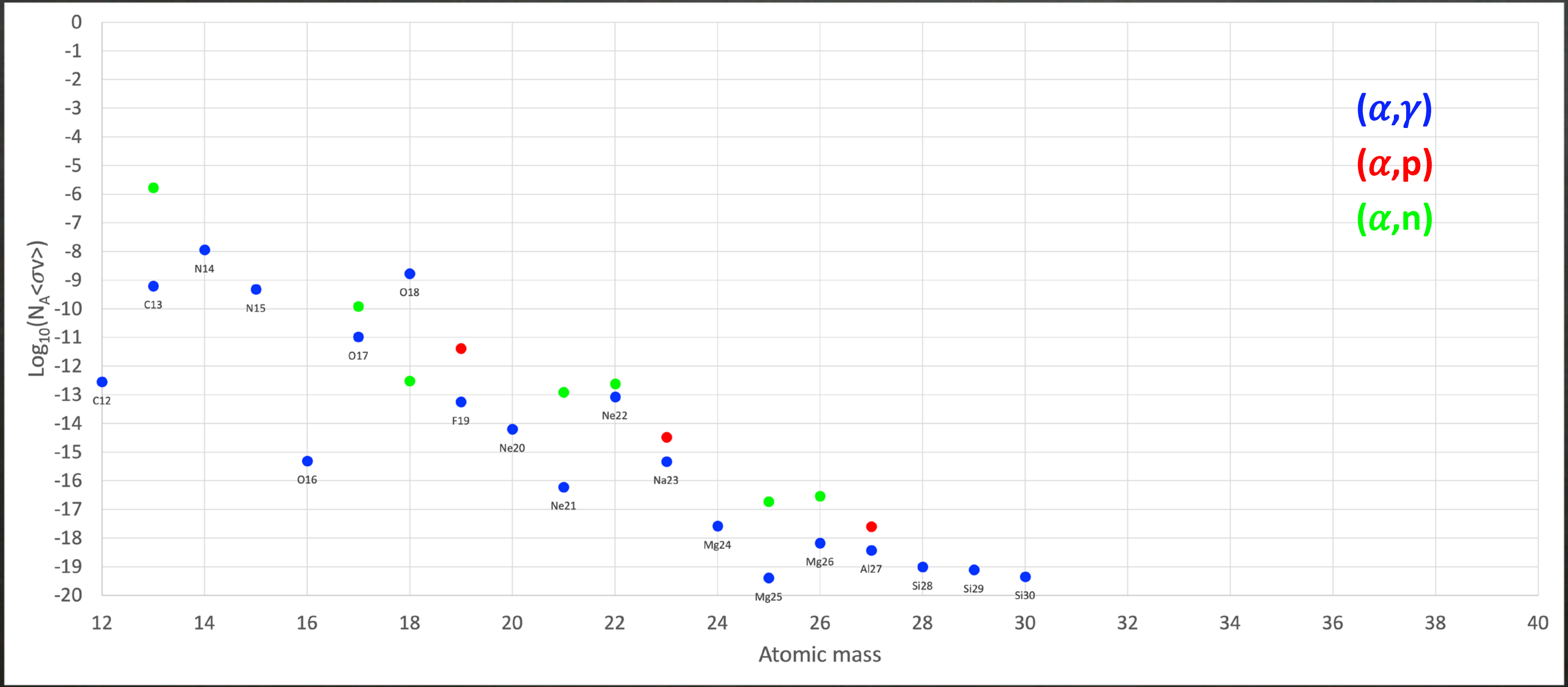


FIG. I,2. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. Elements synthesized by interactions with protons (hydrogen burning) are listed horizontally. Elements synthesized by interactions with alpha particles (helium burning) and by still more complicated processes are listed vertically. The details of the production of all of the known stable isotopes of carbon, nitrogen, oxygen, fluorine, neon, and sodium are shown completely. Neutron capture processes by which the highly charged heavy elements are synthesized are indicated by curved arrows. The production of radioactive Tc^{99} is indicated as an example for which there is astrophysical evidence of neutron captures at a slow rate over long periods of time in red giant stars. Similarly Cf^{254}, produced in supernovae, is an example of neutron synthesis at a rapid rate. The iron group is produced by a variety of nuclear reactions at equilibrium in the last stable stage of a star's evolution.

What about the neutron source(s)?

What about the neutron source(s)?



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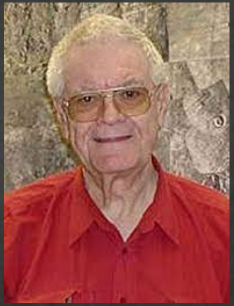

Alastair G. W. Cameron

ORIGIN OF ANOMALOUS ABUNDANCES OF THE ELEMENTS IN GIANT STARS

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Received July 9, 1954; revised September 14, 1954

ABSTRACT

Following the exhaustion of hydrogen in the cores of certain massive stars, it appears that the cores contract and the envelopes expand, the stars becoming red giants. When the central temperature and density have increased sufficiently, thermonuclear reactions involving the helium in the core can take place with the nuclei which have taken part in the carbon cycle. The rate of the $C^{13}(\alpha, n)O^{16}$ reaction is calculated; it is found to produce neutrons rapidly at a temperature of 10^8 ° K and a density of 5×10^4 gm/cm^3. These neutrons are slowed down until they reach thermal equilibrium with their surroundings (neutron energies of about 10 kev) and are then captured by the surrounding nuclei in proportion to their cosmic abundances and neutron-capture cross-sections. The latter quantities are estimated for neutron energies of 10 kev as a function of the mass number of the capturing nucleus. The heavier nuclei each appear to capture many neutrons (about 35 neutrons at mass number 100). Nuclei with closed shells of 50, 82, and 126 neutrons have much smaller cross-sections and become concentrated by the neutron-capture processes. With the assumption of a moderate amount of mixing between core and envelope of the star, it is thus found that the distinctive features of S-type and *Ba* II–type spectra can be explained. The further evolution of the star should then lead to the production of excess carbon by the Salpeter reactions, and the spectrum should gradually turn into that of type R or N.

The $^{13}C(\alpha,n)$ is the process with the highest nuclear cross section but there are not enough ^{13}C nuclei to have a substantial production of neutrons.

But, if we assume a continuous moderate ingestion of protons in the center of the star, we may feed the $^{13}C(\alpha,n)$ nuclear reaction enough to produce a substantial flux of neutrons

1955

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STELLAR EVOLUTION AND THE SYNTHESIS OF THE ELEMENTS

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Received March 7, 1955; revised April 7, 1955

ABSTRACT

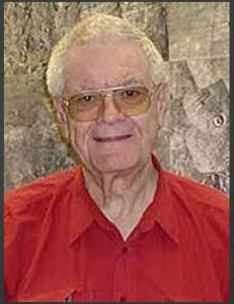
The production of neutrons in stellar interiors will occur through exoergic (α, n) reactions on O^{17}, Ne^{21}, Mg^{25}, and Mg^{26} as well as on C^{13}, as first suggested by Cameron With these reactions as possible neutron sources, an attempt is made to indicate a general, but still qualitative, basis for the synthesis of the elements in stars The importance of successive stages of interaction of the light nuclei with hydrogen and helium is stressed. In particular, the reaction $Ne^{20}(p, \gamma)Na^{21}(\beta^+)Ne^{21}$, followed by $Ne^{21}(\alpha, n)Mg^{24}$, is taken as the basis for alterations and modifications of the mechanisms of Hoyle and Cameron for the synthesis of the intermediate and heavy elements, respectively The use of this reaction obviates some of the difficulties encountered in processes in which a small proportion of hydrogen must be mixed into the stellar core at temperatures at which it will be very rapidly consumed

A possible evolutionary scheme which is consistent with these element-building processes is outlined It is supposed that the synthesis of the heavy elements will take place in stars which have reached the cool giant stage in their evolutionary path. The M as well as the S stars may be important in this connection A rough estimate, based on the observed frequency of S stars, suggests that the rate of element synthesis in these stars is sufficient to produce the observed heavy-element abundances. Differences in chemical composition between population I, population II, and intermediate groups of stars are briefly discussed.

All these nuclei may produce neutrons via an (α,n) process:
^{17}O, ^{21}Ne, ^{25}Mg and ^{26}Mg + ^{13}C

They sponsor the $^{21}Ne(\alpha,n)$ because it may be produced by the abundant ^{20}Ne in H burning via the $^{20}Ne(p,\gamma)^{21}Na(\beta^+)^{21}Ne$

1956



Alastair G. W. Cameron

Cameron, A. G. W. The evolution of the cosmic mixture of elements produced by capture of neutrons.

Thermonuclear reactions of helium with C^{13}, O^{17}, and Ne^{21} provide sources of neutrons in stars with helium cores at temperatures of 0.7 to 2×10^8 °K. The neutrons are thermalized to energies in the vicinity of 10 kev, and are captured by their surroundings.

The changes in nuclear abundances, brought about by capture of these neutrons as they are fed into an initial Suess cosmic mixture, have been followed by numerical integration. The abundances of elements heavier than iron increase rapidly and approach saturation values. The factors of increase saturate at several hundred in the region of mass 80 and at several thousand in the rare-earth region. It is suggested that such a neutron capture process is responsible for producing the large increases in heavy-element abundances observed in the spectra of several classes of stars.

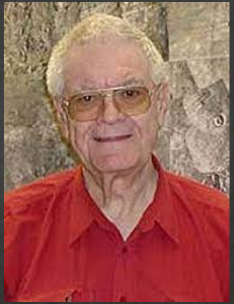
The nuclei remaining after hydrogen exhaustion in the core may at most provide enough neutrons to approach saturation in the mass-80 region, but not in the rare-earth region. The rate of production of these neutrons defines a slow time scale with many thousands of years between successive neutron captures by a given nucleus. However the observed relative abundances of the heavy nuclides cannot have originated in this way. If the heavy elements have originated in stars, then the slow time scale is of only minor importance for the production of nuclides of mass greater than 100. The majority of such nuclei appear to have been produced on a fast time scale for neutron capture—about one hour between successive captures to produce isolated neutron-rich nuclides; about 10 minutes to form heavy trans-lead nuclides. Such a fast time scale for neutron capture implies very high neutron fluxes.

A possible mechanism for the production of these high neutron fluxes may exist in massive stars with fast rotation. If the helium convection zone can extend temporarily to the boundary of the core, then some hydrogen may be transported rapidly toward the center of the star, where in succession C^{13} and neutrons would be produced. The same mechanism may mix neutron-evolved core material into the polar and surface regions of some stars.

slow neutron captures
A<100
(low rotation)

fast neutron captures
A>100
(fast rotation)

1957



Alastair G. W. Cameron

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NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

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Fowler and the Burbidges, disturbed by the problems of mixing and N^{14} competition discussed above, have suggested that an alternate source of neutrons for heavy-element synthesis may be provided by the Ne^{21} (α,n) Mg^{24} reaction.[10] This requires that most of the Ne^{20} present in the initial composition of the star would have been converted to Ne^{21} in the hydrogen shell source, which is at present uncertain.

TABLE I

MECHANISMS OF NUCLEOGENESIS

Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors
	2. Neutron capture on slow time scale
	3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements:	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae
	2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

1956

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Origin of the Elements in Stars

F. Hoyle, William A. Fowler,
G. R. Burbidge, E. M. Burbidge

Experimental (*1, 1a*) and observational (*2–6*) evidence has continued to accumulate in recent years in support of the theory (*7–10*) that the elements have been and are still being synthesized in stars. Since the appearance of a new and remarkable analysis by Suess and Urey (*11*) of the abundances of the elements, we have found it possible to explain, in a general way, the abundances of practically all the isotopes of the elements from hydrogen through uranium by synthesis in stars and supernovae. In this article we wish to outline in a qualitative fashion the essentially separate mechanisms which are required in stellar synthesis (*12*).

thesis would not be possible. In theories of primordial synthesis, the break in the neutron-capture chain at He^4 has been an insuperable stumbling block. In contrast, it is the saving factor in stellar neutron synthesis. We emphasize that there

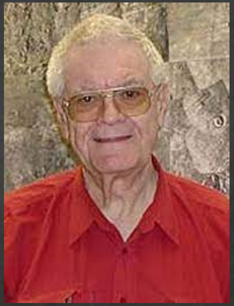
At temperatures from about 10^7 to 5×10^7 degrees in main-sequence stars, hydrogen is transformed to helium, $4H^1 \rightarrow He^4$, with an average binding energy of 7.07 million electron volts (Mev) per nucleon. We emphasize that the proton-proton sequence of reactions makes possible the production of helium starting only with hydrogen. The recent discovery of the free neutrino as reported by Cowan *et al.* (*1a*) leads to increased confidence in the existence of the primary proton-proton interaction which proceeds through prompt electron-neutrino emission. At temperatures from 10^8 to 2×10^8 degrees in red giant stars, He^4 is transformed principally to C^{12}, O^{16}, and Ne^{20} with an average binding energy of 7.98 Mev per nucleon. The important roles of the ground state of Be^8 and of the second excited state of C^{12} in expediting the primary process of helium fusion, $3He^4 \rightarrow C^{12}$, have recently been clarified (*1*), and it is now clear that the long-standing difficulties in element synthesis at mass 5 and mass 8 are bypassed in this process. At temperatures of the order 10^9 degrees, Mg^{24}, Si^{28}, S^{32}, A^{36}, and Ca^{40} are formed from the carbon, oxygen, and neon, the average binding thus rising to 8.55 Mev per nucleon, while, at temperatures from 2×10^9 to 5×10^9 degrees, Fe^{56} and neighboring nuclei are synthesized, yielding an average binding energy of 8.79 Mev per nucleon. No higher binding than this exists,

The situation, then, is that a thermal "cooking" of pure hydrogen yields principally He^4 and the α-particle nuclei with $A=4n$, $Z=2n$, $n=3, 4, 5, 6, 7, 8, 9$, and 10 (C^{12} to Ca^{40}), together with nuclei centered around Fe^{56}. These are the most abundant nuclei. Moreover, the relative

During the $H \rightarrow He^4$ stage of second-generation stars, Ne^{20} is processed by the reactions $Ne^{20}(p,\gamma)Na^{21}$, $Na^{21}(\beta^+)Ne^{21}$. During the latter stage of the phase, $He^4 \rightarrow C^{12}, O^{16}, Ne^{20}$, free neutrons are generated by $Ne^{21}(\alpha,n)Mg^{24}$. The free neutrons are partly added to the light elements with $A=4n$, producing the remaining isotopes of these elements, and are partly added to Fe^{56} and allied nuclei. Because the Fe^{56} is present in only very low abundance, the number of neu-

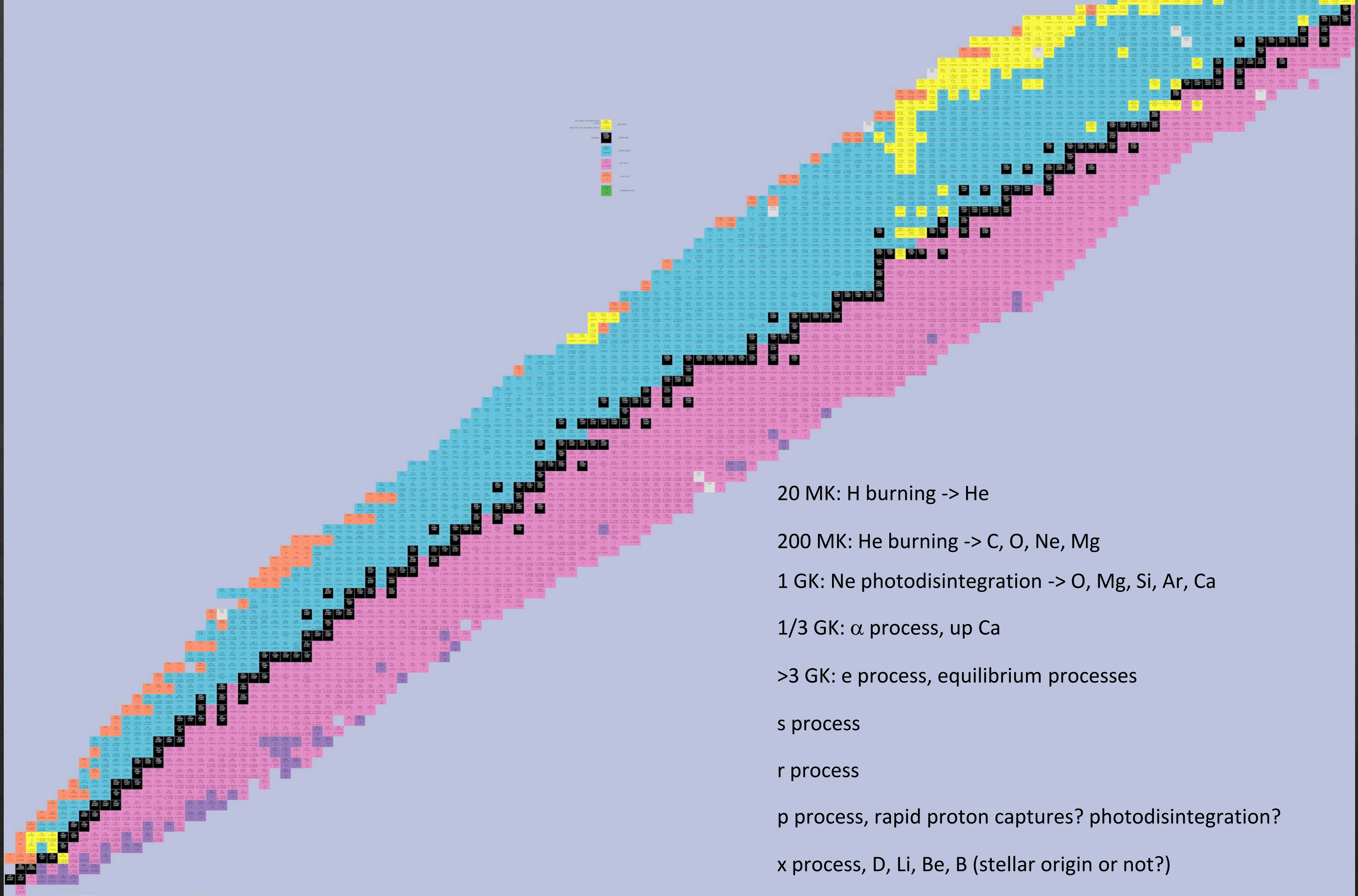
We have distinguished two conditions under which the neutron capture can take place, a slow (*s*) process and a rapid (*r*) process. Suess and Urey (*11*) and Coryell (*13*) have already pointed out that the peaks in the abundance curves at stable nuclei with filled neutron shells ($A=90, N=50$; $A=139, N=82$; $A=208, N=126$) strongly indicate the operation of the *s*-process in element synthesis and that the nearby peaks at $A=82$, 130, and 194, shifted by $\delta A \sim 8$ to 14, similarly require the operation of the *r*-process. The *s*-process we associate with giant stars that evolve in approximately 10^5 years. We regard the observed presence (*2*) of technetium in the atmospheres of the giant S-type stars as a demonstration that the building of very heavy elements by neutron addition actually takes place in stars. The *r*-process we associate with the explosion of supernovae, the time scale being as small as 10 to 100 seconds. We regard the

1960



Alastair G. W. Cameron

New Neutron Sources of Possible Astrophysical Importance. A. G. W. Cameron, *Mount Wilson and Palomar Observatories.*—The helium-burning neutron sources previously discussed seem inadequate for heavy-element formation by neutron capture on a slow time scale, owing to the probable small abundances of C^{13} and Ne^{21} following hydrogen thermonuclear reactions in a stellar interior. These convert most of the original C, N, and O nuclei into N^{14}. However, when helium-burning starts, the reactions $N^{14}(\alpha,\gamma)F^{18}(\beta^{+}\nu)O^{18}$ and $O^{18}(\alpha,\gamma)Ne^{22}$ should readily take place. Temperatures near 2×10^{8} °K are needed to destroy Ne^{22}; if these should be available near the end of helium-burning, then the reactions $Ne^{22}(\alpha,\gamma)Mg^{26}$ and $Ne^{22}(\alpha,n)Mg^{25}$ should occur with comparable probabilities. The latter reaction is



20 MK: H burning -> He

200 MK: He burning -> C, O, Ne, Mg

1 GK: Ne photodisintegration -> O, Mg, Si, Ar, Ca

1/3 GK: α process, up Ca

>3 GK: e process, equilibrium processes

s process

r process

p process, rapid proton captures? photodisintegration?

x process, D, Li, Be, B (stellar origin or not?)

So, what remains at the end of the 50's?


1961, One Hundred and One Dalmatians