II. JOINT DISCUSSION ON NUCLEOGENESIS IN STARS
(20 August 1958)

ORGANIZING COMMITTEE: Prof. W. A. Fowler (*Chairman*), Prof. F. Hoyle and Dr A. G. Masevich.

CHAIRMAN: Prof. W. A. Fowler.

SECRETARY: Prof. D. A. Frank-Kamenetsky.

INTRODUCTORY REMARKS

WILLIAM A. FOWLER

Members and guests of the International Astronomical Union, ladies and gentlemen, it gives me great pleasure to welcome you to the Joint Discussion on 'Nucleogenesis in Stars'. Let me first of all express my appreciation for the help given me by the other two members of the organizing committee, Dr A. G. Masevich of the U.S.S.R. and Prof. F. Hoyle of Great Britain. I am also very grateful to Prof. D. A. Frank-Kamenetsky who has consented to serve as secretary of the meeting.

I would like to take this opportunity to make some introductory remarks concerning nucleogenesis in stars and to sketch the outline of the program. Fig. 1 shows schematically the various nuclear processes by which all the elements and their isotopes may be synthesized in several generations of stars starting with pure or almost pure hydrogen as the composition of the first stars which formed in the Galaxy. In the figure, hydrogen burning reactions are plotted horizontally, helium burning and more complicated processes are plotted vertically. Neutron capture processes are shown as curved arrows.

Starting with pure hydrogen in the upper left-hand corner, nuclear reactions are now known which will convert the hydrogen into helium. These reactions occur during the main sequence stage of evolution of the first stars and are designated as the proton-proton or pp-chain. It is important to emphasize that helium can be synthesized from *pure* hydrogen. In this discussion, we will not attempt to explain the origin of the hydrogen. Perhaps the 6-BeV accelerator at Berkeley, or the 10-BeV accelerator at Dubna, or the 25-BeV accelerator under construction at Brookhaven will some day answer this problem.

In the red-giant stage of the first stars, the helium ash from hydrogen burning is converted into ^{12}C, ^{16}O, and ^{20}Ne. The hydrogen [1] and helium burning will be discussed by Professor E. E. Salpeter. At a later and probably short-lived stage of stellar evolution, the ^{12}C, ^{16}O, and ^{20}Ne will be processed into alpha-particle nuclei heavier than ^{20}Ne and even into the iron group elements such as Ti, V, Cr, Mn, Fe, Co, and Ni. These processes will be discussed by Dr T. Hatanaka, Dr Nemirovsky and Prof. Hoyle.

It is essential to the theory of nucleogenesis in stars that the elements produced in stars be ejected at some stage of stellar evolution into the interstellar gas from which second and later generation stars can be formed. Thus ^{12}C, ^{16}O, and ^{20}Ne will be processed by hydrogen in the main sequence stage of these later stars and it is important to note that cyclic processes occur which produce all of the isotopes of the light elements and that these survive the hydrogen burning because of the cycling as shown in the figure. ^{15}N produced from ^{12}C through ^{13}C and ^{14}N reverts to ^{12}C while ^{23}Na produced from ^{20}Ne through ^{21}Ne and ^{22}Ne reverts to ^{20}Ne. This is not at all the case for deuterium, lithium, beryllium and boron which are destroyed in stellar interiors and are perhaps produced in stellar surfaces as will be discussed by Dr Tverskoy.

In the red-giant stage of these later stars the ^{13}C, ^{17}O, and ^{21}Ne produced in hydrogen burning react with helium to produce neutrons. These neutrons are captured by the iron group elements to form certain of the isotopes of the heavy elements on a slow time-scale as will be discussed by Dr A. G. W. Cameron. The appearance of technetium, which has only radioactive isotopes, in S-giants is taken as evidence for this so-called *s*-process. The

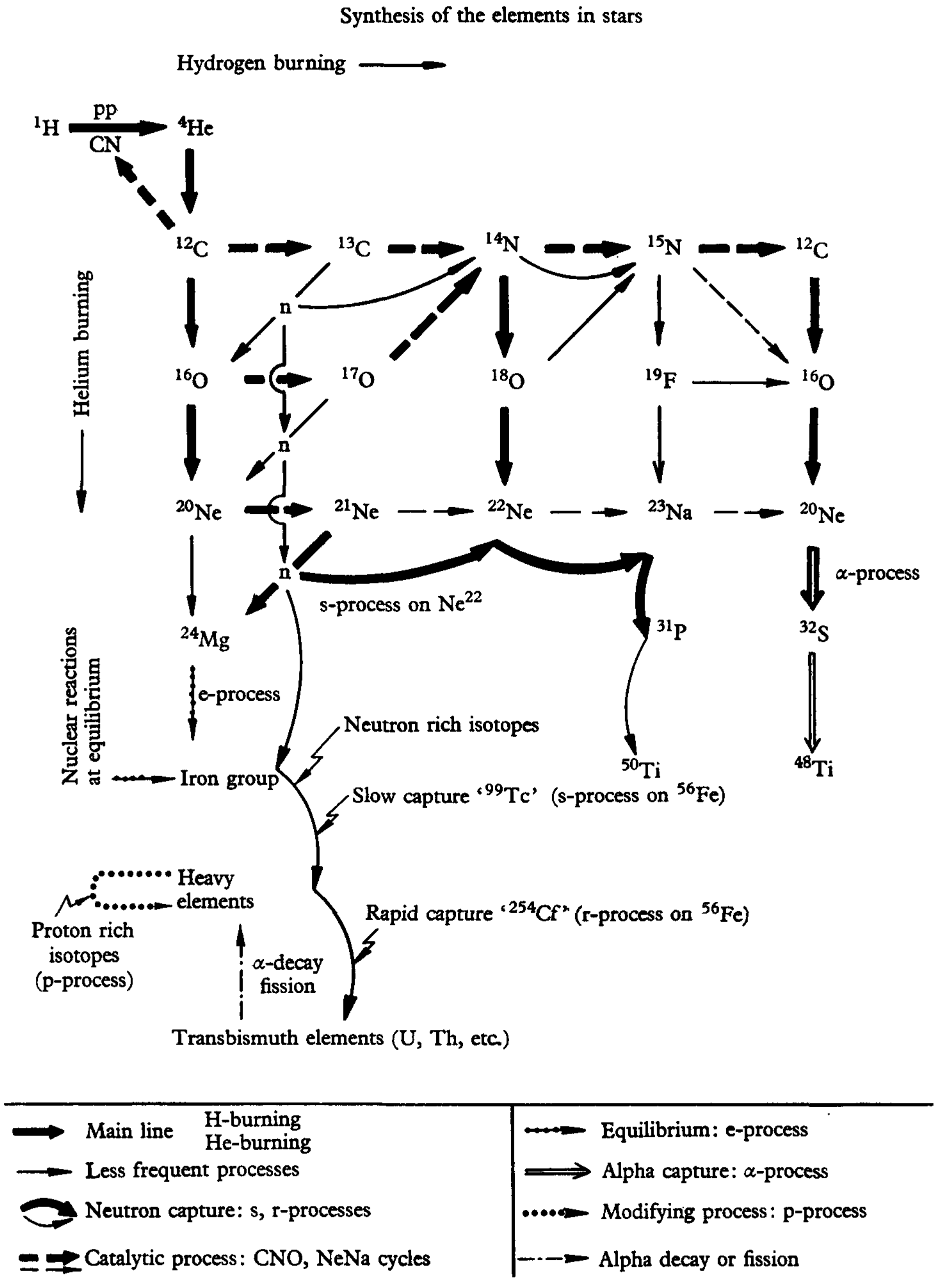

Fig. 1. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. The rapid and continued increase in our knowledge of these processes will be found by reference to previous versions of this diagram in the following references: *Ap. J.* **122**, 271, 1955; *Sci. Mon.* **84**, 84, 1957 and *Rev. Mod. Phys.* **29**, 547, 1957.

over-abundances of certain elements produced in peculiar stars by this process will be discussed by the Drs Burbidge.

Certain neutron-rich isotopes of the elements cannot be produced on a slow time-scale but must be produced rapidly at great neutron fluxes, and Professor Hoyle will discuss super-novae as the site of such events. The existence of radio-active elements such as uranium and thorium in nature and the production of ^{254}Cf both in hydrogen bombs and in super-novae is taken as evidence for this so-called *r*-process.

It will be clear that there are many unsolved problems in this field and these will be emphasized by Prof. Frank-Kamenetsky. Finally, the connexion between nucleogenesis in stellar surfaces and the injection mechanism for cosmic-ray acceleration will be discussed by Dr R. Z. Sagdeyev.

REFERENCE

[1] 'New Theoretical and Experimental Results on Hydrogen Burning in Stars' by W. A. Fowler (presented by E. E. Salpeter) has been omitted from this report. The material is covered in 'Origin of the Nuclear Species' by W. A. Fowler, a chapter in *Modern Physics for the Engineer*, Vol. II, ed. by L. N. Ridenour, published by McGraw-Hill Book Company, New York, 1959.

1. NEW THEORETICAL AND EXPERIMENTAL RESULTS ON HELIUM AND HEAVY ION BURNING IN STARS

E. E. SALPETER

In recent review articles [1, 2] general surveys will be found on the series of thermonuclear reactions which can lead all the way from pure helium to the elements around the 'iron-peak' at temperatures between $0{\cdot}5\times10^8$ °K and 50×10^8 °K. The reaction chain $3\mathrm{He}^4 \rightarrow {}^{12}\mathrm{C}(\alpha, \gamma){}^{16}\mathrm{O}; {}^{16}\mathrm{O}(\alpha, \gamma){}^{20}\mathrm{Ne}$, which proceeds at temperatures of about 1×10^8 °K, has been investigated in detail a year or two ago [3, 4]. Although some of the relevant numbers are now known slightly more accurately, the main conclusions and uncertainties remain the same. It is still not known whether the 4·95 MeV level in ^{20}Ne has the right spin and parity to contribute to the $^{16}\mathrm{O}(\alpha, \gamma)^{20}\mathrm{Ne}$ reaction. If it does, the main reaction products of helium heated to about 1×10^8 °K are ^{12}C and ^{20}Ne; if it does not, mainly ^{12}C. In either case the amount of ^{16}O produced is probably fairly small [2] and the production of ^{24}Mg is probably negligible. We now have further evidence [5, 6] that the 7·65 MeV level in ^{12}C, which is of great importance for the key reaction $3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}$, has indeed the spin-parity 0^+ as assumed in previous calculations. The absolute values of reaction rates for $3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}$ are still uncertain by about a factor of 10.

Let me digress a moment to the astrophysical significance of the reaction converting three helium-nuclei into a single ^{12}C-nucleus, which I have just discussed and which is the key reaction for the formation of heavier elements out of helium. Although this reaction proceeds easily in the interior of certain red giant stars, it *cannot* proceed in the first few seconds or minutes of the expansion of the universe as a whole (even if one believes in that type of cosmology). The difference is one of density, the triple alpha-particle reaction being rather density-dependent. At the very early, dense and very hot, stages of the expansion of the universe, nuclear synthesis is inhibited by nuclear photo-disintegration. At slightly later stages when photo-disintegration becomes less important, the density has become much too low for the conversion of helium into carbon (or into anything else). In stars, on the other hand, densities are quite adequate. Thus, for building all elements heavier than helium, the original expansion of the universe is, from the nuclear point of view, simply useless.

Qualitative discussions of the thermonuclear reactions ensuing when ^{12}C, ^{16}O and ^{20}Ne are heated to temperatures of more than about 5×10^8 °K were already available a few years ago [7, 8]. It is now possible to make more quantitative calculations.