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 0.5×10^8 °K and 50×10^8 °K. The reaction chain $3He^4 \to {}^{12}C(\alpha, \gamma){}^{16}O$; ${}^{16}O(\alpha, \gamma){}^{20}Ne$, 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 ${}^{16}O(\alpha, \gamma){}^{20}Ne$ 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 $3{}^4He \to {}^{12}C$, has indeed the spin-parity O$^+$ as assumed in previous calculations. The absolute values of reaction rates for $3{}^4He \to {}^{12}C$ 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.

JOINT DISCUSSION

One important type of reaction involves the formation of a compound nucleus in the collision between two medium-light nuclei, the reactions of greatest astro-physical interest being (^{12}C + ^{12}C) and (^{16}O + ^{16}O). Calculations of the rates of such reactions are most sensitive to the effective interaction-radius between the two nuclei. Although no experiments on the actual reactions of interest are as yet available, one can estimate the relevant radii indirectly from experimental results on similar reactions involving some-what different nuclei. Another important type of reaction involves a succession of (γ, α) photo-disintegration and (α, γ) alpha-capture reactions on various nuclei produced previously. Rates for these reactions can be calculated by methods analogous to those used previously [3, 4] for the 'alpha-burning' reactions. The temperatures T at which the lifetimes of ^{12}C, ^{20}Ne and ^{16}O, respectively, are 10^5 years (for concentrations of 10^5 gm/cc) are given below, together with the key reaction destroying each nucleus:

$$^{12}\text{C} + {}^{12}\text{C}: \quad T = (5\cdot7 \pm 0\cdot7) \times 10^8 \text{ °K};$$

$$^{20}\text{Ne} (\gamma, \alpha): T = (11\cdot7 \pm 0\cdot7) \times 10^8 \text{ °K};$$

$$^{16}\text{O} + {}^{16}\text{O}: \quad T = (12\cdot5 \pm 1\cdot4) \times 10^8 \text{ °K}.$$

It is hoped that some crucial experiments will be carried out soon which will improve the accuracy of these numbers.

The key reactions listed above are followed by various reactions involving alpha-particles, protons and neutrons. The most important reaction products are: In the destruction of ^{12}C at about 600 million degrees: mainly ^{16}O, ^{20}Ne and ^{24}Mg, with smaller amounts of ^{23}Na. According to recent experiments, the amounts of sodium produced are not as small as was estimated four or five years ago. In the destruction of ^{16}O and ^{20}Ne at about 1·3 billion degrees the main products are ^{28}Si and ^{32}S. However, smaller amounts of very many isotopes with atomic weight up to around 30 are also produced.

At temperatures of about two or three billion degrees, a multitude of competing reactions begin to take place, which can transform ^{24}Mg, ^{28}Si and ^{32}S into the nuclei near the 'iron peak'. Quantitative calculations have not proceeded very far as yet, but preliminary indications are that at these temperatures only very small amounts are produced of the nuclei somewhat lighter than the iron peak ones, in particular of the isotopes of argon and calcium.

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