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6. ON SOME UNSOLVED QUESTIONS IN THE THEORY OF THE ORIGIN OF THE ELEMENTS

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In the preceeding reports an elegant theory of the origin of the elements has been outlined. This theory aims to be a comprehensive one. With the exception of D, Li, Be, B, the origin of all other nuclides is explained by thermonuclear reactions and subsequent neutron capture.

But some difficulties arise in connexion with two groups of nuclides: the iron peak and the by-passed nuclei.

The possible modes of formation of the by-passed nuclei are (γ, n), $(\gamma, 2n)$ ...; $(n, 2n)$, $(n, 3n)$ ...; (p, n), $(p, 2n)$ ..., and (p, γ) reactions.

Of all the processes listed only the (p, γ) process has no energy threshold and may proceed in a sub-barrier thermonuclear fashion. It was hitherto assumed that by-passed nuclei are formed by 'p-process' consisting of a sequence of such rapid thermal (p, γ) reactions.

In order to penetrate the high barriers involved, the temperature must be of the order of several billion degrees. At such temperatures the reactions become reversible. So the p-process turns out to be a sequence of rapid thermal reversible reactions. According to the principle of microscopic reversibility such reactions must inevitably lead to a thermodynamic equilibrium.

We do not mean total equilibrium between all nuclides, but a partial equilibrium between by-passed nuclides and their isobars on the main path. A simple analysis of observed abundances shows the absence of such equilibrium for all by-passed nuclides besides the iron peak.

Let us see which non-equilibrium, slow processes are possible. The capture of a proton is followed by emission of a γ-quantum only if the energy of the compound nucleus is lower than that needed for the emission of a neutron. If the energy exceeds this threshold the (p, n) reaction sets in and radiative capture becomes negligible. The threshold for (p, n) reactions is very high for light nuclei and drops sharply near $A = 50$. At higher mass numbers there is a number of nuclides for which the principal reaction with protons is (p, n) in the energy range near 2 MeV. After the next energy threshold near 10 MeV is surpassed the $(p, 2n)$ reaction sets in. These processes may provide an additional source of neutrons for the main line of nuclear synthesis by slow neutron capture.

Let us consider the following curious process: a (p, n) reaction with subsequent transition back to the initial nucleus by positron emission or electron capture. This leads ultimately to net transition of protons into neutrons. If the neutron width is much larger than the radiation width, the nuclei are not consumed and act as a catalyst. If these nuclei can be formed by slow neutron capture, the process acquires an auto-catalytic character. The nucleus generates neutrons for its own synthesis. If $(p, 2n)$ is important, the formation of heavier nuclei stops and concentration of the nucleus near the low (p, n) threshold grows exponentially. This may be regarded as a plausible non-equilibrium explanation of the iron peak. From the values of (p, n) threshold energies it can be seen that neutron capture should cease at the nuclei ^{55}Mn, ^{57}Fe and ^{59}Co. These should be transformed into their most abundant neighbours ^{54}Fe, ^{56}Fe and ^{58}Ni by subsequent $(p, 2n)$ reactions, followed by β-decay in case of ^{56}Fe.

Another proposal for a non-equilibrium explanation of the iron peak is given in the paper by Dr Nemirovsky.

The formation of by-passed nuclei is easily explained by (p, $2n$) reactions with 10 MeV-protons.

As one of the difficulties it may be noted that in some cases a single (p, γ) process followed by β-decay is sufficient, but no marked increase in abundance is observed. This requires a proton spectrum poor in protons below the (p, n) threshold.

The required protons in the energy range 2–10 MeV in non-equilibrium conditions cannot be of a thermal origin. They must be attributed to cold acceleration.

For the case of nuclear reactions, acceleration of particles in a plasma, and not in a vacuum, is required. Then effective acceleration is possible only at initial ion velocities, beginning with a value not lower than the velocities of thermal electrons. With lower velocities the energy gained is wasted through electronic friction. It follows that the mechanism of cold acceleration must consist of two stages: primary gas-dynamical injection and subsequent electromagnetic acceleration.

The preliminary gas-dynamical acceleration can be effected by shock waves on their passage into a medium of decreasing density (density cumulation as we call this mechanism). The energy attained depends critically upon the thickness of the shock front. This problem is considered in detail by Dr Sagdeyev in his paper.

We see that nuclear reactions at stellar surfaces require a combination of shock waves and electromagnetic fields.

The products of nuclear reactions can be detected spectroscopically only under the condition that they accumulate at the surface of the star. But they are very likely to be ejected by shock waves into interstellar space, or carried into the stellar interior by turbulent diffusion. The latter problem is treated by Dr Tverskoy in a paper that follows.

We have now to look for cosmic objects in which cold acceleration processes might lead to nuclear reactions. In the first place these may be the non-stationary red dwarfs, or the so-called flare-stars. We know from the theory of internal constitution that they have very deep convection zones comprising a large part of the whole volume. Large flares and polarization in the continuous spectrum are signs of gas-dynamical and magnetic activity. The second group might include the Wolf-Rayet stars and cores of planetary nebulae, since shock waves seem to provide the most effective mechanism for the ejection of matter.

On the contrary, peculiar A-stars (magnetic variables) do not show signs of gas-dynamical activity. They should be regarded as objects in which the products of a previous active stage are frozen at the surface due to the formation of a general magnetic field. The fact that they are localized near the intersection of the horizontal branch with the main sequence, seems to give support to the view stated.

It is generally accepted that D, Li, Be, B are formed by cold acceleration processes in stellar atmospheres. We have attempted to collect some evidence in favour of a wider role of these processes. It seems that they might be responsible for the iron peak and for the genesis of by-passed nuclei.

Laboratory work on controlled thermonuclear reactions has shown that it is much easier to achieve a nuclear reaction due to cold acceleration processes than a genuine thermonuclear reaction. This result may also have some significance for astrophysics.

7. ON THE MECHANISM OF PRELIMINARY PARTICLE ACCELERATION IN RAREFIED STELLAR ATMOSPHERES

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In the problem of nuclear reactions in stellar atmospheres, produced by cold accelerations, as well as in the problem of the origin of cosmic rays, the question of injection is not yet clear.