Feasibility of thermonuclear fusion of elements

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The feasibility of fusion of various elements is discussed on the basis of an extrapolation of the known conditions of controlled thermonuclear fusion.

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The feasibility in principle of fusing any element in the laboratory or even on a commercial basis is evidenced by the results of astrophysics and physics, especially the progress in research on controlled thermonuclear fusion.[1–8] The analysis in this paper is confined to methods of inertial containment of a superdense plasma produced in special compression regimes.[6–14] For a target with mass M and with a shape close to spherical, the necessary value of the "optical thickness" $\langle\rho R\rangle \approx M^{1/3}\langle\rho\rangle^{2/3}$ is reached by superdense compression,[6] preferably isentropic, with a peak power of the external action (say by a laser) $\dot{E} \sim (\rho R)^2$.[11] The initiating temperature is obtained by means of a controlled increase of the entropy.[6–8]

The known fusion conditions $DT \to {}^4He + n$ ($\langle\rho R\rangle = 2$–5 g/cm^2, $\rho_{max} \approx 10^3$ g/cm^3, and $T_i \cong 5$–10 keV) can be attained by applying a pulse $E \cong 0.1$–1.0 MJ with maximum power $\dot{E} \gtrsim 10^{14}$ W.[7,14] Initiation of a small fraction of fuel with $(\rho R)_f \gtrsim 1$ g/cm^2 is sufficient for appreciable burnup.[6–8,10,12]

In contrast to exothermal processes of controlled thermonuclear fusion, universal fusion of elements includes reactions both with small energy release and with considerable energy absorption.[1,2,6] One should expect here more stringent requirements: $50 \gtrsim T \gtrsim 500$ keV and $\langle\rho R\rangle \gtrsim 100$ g/cm^2. If the pulse energy is limited $E \gtrsim 100$ MJ,[16] then a density $\rho \gtrsim 10^5$ g/cm^3 is required, and can be obtained by shaping pulses up to a power $\gtrsim 10^{17}$ W (possibly with tuning of the frequency during the compression).

The required power can apparently be decreased by using targets with quasi-one-dimensional compression of distributed elements (dense plasmoids) accelerated to 10^{8-9} cm/sec, in accordance with the relation $\rho^{max}/\rho_0 \approx [(\gamma-1)u^{max}/2a_0^{ac}]^{2/(\gamma-1)}$.[11]

The energy of the required acting pulse can be decreased by one or two orders of magnitude by using cumulative[5,6,9,12] phenomena, and also by reaching already in the course of the acceleration[10] values of $\langle \rho R \rangle$ at which heat release sets in and imparts[8,14] an additional velocity to the internal shell with increased values of A and T_p. This fills the gap between the combustion temperature T(DT) $\gtrsim 100$ keV[6,8] and $T \gtrsim 200$ keV needed to "cook" most elements in the range up to iron.

The hydrodynamic multistage character of the type considered in[9] is of interest more readily for the use of more "refractory" targets rather than larger targets.

A "chemical" method of overcoming the same difficulty is multistage initiation with overlap of the combustion and initiation temperatures: DT= >DD = >$H^{11}B \rightarrow 3\,^4He + 8.7$ MeV ($\rho \gtrsim 10^5$ g/cm^3, and $\rho R \gtrsim 100$ g/cm^2). The last reaction[1,6] is of interest because it is convenient to use, has a 99.9% yield of α particles, can be used for thermostatic control of universal fusion of elements, and also because there is much more boron on earth than deuterium. About half of the obtained energy (≈ 70 J/ng $H^{11}B$, $1 \lesssim E_\alpha \lesssim 4$ MeV) can be diverted to fusion $^4He + ^{18}O \rightarrow ^{22}Ne + \gamma$, which absorbs ≈ 20 J/ng of ^{22}Ne. This process, however, is not optimal.

If the initial element is helium, then the equilibrium products of its "cooking" at $\rho \approx 10^5$ g/cm^3, $100 \lesssim T \lesssim 500$ keV, can contain up to several percent of nickel, titanium, argon, and sulfur, which are conserved as a result of the effect of "frozen equilibrium."[1,2]

Up to iron or nickel, the elements are produced by combustion of lighter ones. The next elements are obtained by capture of α particles and neutrons, the source of which may be the energywise highly unprofitable reaction[1,6]

$$^{56}Fe \rightarrow 13\,^4He + 4n \rightarrow \text{"everything"} \quad (\rho \approx 10^5 \text{ g/cm}^3, \quad T \gtrsim 300 \text{ keV}).$$

In its products, close enough to local equilibrium, by virtue of the abundance of neutrons and the impossibility of the fusion of an α particle with a neutron, a recombination fusion of elements takes place with mass numbers near the peaks $A = 80$, 130, 195 (not excluding also the fusion of superheavy elements).[2]

Contributing to high densities in the processes considered above is the energy "drain" (up to ≈ -100 J/ng) to dissociation of nuclei, the production of equilibrium photons, neutronization of matter, and pair production.[1,2,6,16] These phenomena lead to a decrease of the effective Poisson adiabatic exponent γ from 5/3 to 4/3—1, i.e., to an appreciable enhancement of the compression by pulses of given energies.[10,11]

For a "ladder-type" evolution of isotopes in the direction of the "stability islands" of the suerpheavy elements,[6] interest attaches to multiple superdense processing of the "thermonuclear ashes" with maintenance of the β-decay times. "Forced" β^+ decay in a dense medium of strongly degenerate electrons[15] might lead to the solution of the problem of decreasing these times.

Universal fusion of nuclei is best divided into three categories: high-power exothermal (on the whole) processes, analogous to ordinary controlled thermonuclear fusion, with "cooking" of small impurities—the initial elements for the production of new ones; "cooking" with small positive or zero energy balance (cf. [16]); endothermal processes, which do not exclude the use of hydrodynamic energy of the dispersal of the fusion products.

The excess energy of the universal-fusion processes can be used also on the basis of known[6] principles of utilization of controlled thermonuclear fusion (a utilization most effective for charged products of the reactions in isentropic compression[6,11]) and on the basis of new principles, for example, with realization of stimulated recombination γ radiation.

The practical solution of the problem of effective fusion of short-supply isotopes of nuclei such as H, He, B, C, O, Si, and Fe depends in many respects on further progress in the "architecture" of targets with stable and productive superdense compression.

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