Utilization of the nuclear energy of the light elements

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It is proposed to utilize for explosive purposes the nuclear reaction of the transmutation of deuterium into hydrogen and tritium realized by a detonation method.

INTRODUCTION

It is very desirable to broaden the circle of elements the nuclear reaction of which can be utilized practically for power production or explosive purposes. Up until now the known processes of practical utilization of a nuclear reaction were based on the realization of the fission chain reaction: the reaction here takes place under the action of neutrons, in the reaction additional neutrons are produced.

The nuclear reaction of fission occurs only in the case of uranium, thorium, and new elements formed from uranium and thorium.

It is well known that the energies of the nuclear reactions of the light elements per unit mass are in a number of cases greater than the energy of the fission of heavy nuclei. Thus, the energy stored in light elements is no less than that in thorium or uranium.

The nuclear reactions of the light elements have been examined as sources of energy in the stars.

The processes proposed for stellar reactions are distinguished by the fact that they involve beta-decay which requires considerable time; therefore their realization under terrestrial conditions is impossible.

However, one can propose a number of other reactions without beta-decay leading to the release of a part of the nuclear energy of the light elements. In all cases for the utilziation of nuclear energy of the light elements it is necessary to carry out a nuclear reaction of similarly charged nuclei. The reaction of similarly charged nuclei always requires a definite minimum energy of the colliding nuclei; at a lower energy of collision the probability of the reaction falls sharply.

On the other hand, a charged particle much more frequently exchanges energy with electrons and nuclei rather than entering into a nuclear reaction. Therefore under ordinary conditions (at not too high temperatures) only a small fraction of the charged particles to which an initial energy was provided will enter into a nuclear reaction, so that the reaction will be a damped one.

The nuclear reaction will proceed without being damped only at very high temperatures of the entire mass, since only in that case the average loss of energy of a charged particle is compensated by the inverse process of the transfer of energy from highly heated electrons and nuclei to the particle under consideration.

The energy of the nuclear reaction distributed over all the nuclei and electrons comprising the system amounts for many reactions to 1–2 MeV.

Thus, this energy suffices to excite a rapid nuclear reaction.

Under a complete thermal equilibrium a considerable portion of the energy is converted into radiation; this circumstance limits the equilibrium average energy of charged particles to the amount of 5000–15000 eV, totally insufficient for carrying out a fast nuclear reaction.

A slow nuclear reaction of light elements at an averege energy of about 10000 eV is practically impossible for the reason that the removal of energy by radiation in the course of a slow reaction leads to a rapid fall of temperature and a complete cessation of the reaction.

CONDITIONS FOR CARRYING OUT THE REACTION

Based on the foregoing we propose the realization of a reaction under conditions that are distinguished by:

a) a high reaction energy per particle;

b) a low energy required to carry out the reaction with a large cross section for the interaction; for this it is desirable to use reactions of nuclei with a low charge;

c) the reaction being carried out in a system with the lowest coefficients of absorption and emission of x-rays with the aim of obtaining a nonequilibrium distribution in which the entire energy would be confined as much as possible in the kinetic energy of the charged particles, while the amount of energy transferred to radiation would be a minimum; for this purpose it is also required to use nuclei with a low charge;

d) the realization of a reaction of the detonation type.

The meaning of this condition consists of the fact that a shock wave is propagated throughout the mass of the reacting substance; the energy of heating in the shock wave is of the same order as the energy of the reaction. Heating in the shock wave occurs during a very short period of time of the order of the flight time of the charged particles. Following this, the material heated in the shock wave reacts, liberating energy and expands pushing the shock wave in front of itself. The process gives in principle the possibility of an explosion of an unlimited amount of the light element suitable for the reaction from a prescribed sufficiently powerful initial pulse.

We emphasize, that forming an opinion on the possibility of an explosive nuclear reaction is associated with the application of the modern detonation theory that has been developed in the Institute of Chemical Physics.

A SPECIFIC PROPOSAL

As a system satisfying the conditions outlined above we propose deuterium; in the detonation of deuterium the following reactions take place

$$...\mathrm{D} + \mathrm{D} = \mathrm{H} + \mathrm{T} + 4\ \mathrm{MeV},$$

$$...\mathrm{D} + \mathrm{D} = \mathrm{n} + \mathrm{He}^3 + 3.2\ \mathrm{MeV},$$

Of particular value is the circumstance that due to the low charge of the nuclei considerable cross sections for the reaction are obtained already at a low energy ($5\cdot 10^{-26}\ \mathrm{cm}^2$ for each reaction at a collision energy with respect to the

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center-of-mass of 200 keV). For the same reason the transformation of kinetic energy into radiation is quite small and amounts at an average energy of approximately 200 keV to approximately 1/5 of the energy released in the nuclear reaction.

The minimum diameter of the long charge of the deuterium, according to the available data on the dependence of the cross section of the reaction on the energy of the particles, cannot exceed 30 cm. For the basis of these numbers, see the Appendix.

The greatest possible density of deuterium is desirable, and this should be realized by using it under high pressure.

In order to facilitate the initiation of a nuclear detonation it is useful to employ massive enveloping shells delaying the dispersal.

The most difficult problem is the problem of ignition, since in uranium or in plutonium the explosion develops relatively slowly and correspondingly quite a significant portion of the energy of the explosion has time to be transformed into radiation, as a result of which the temperature and the pressure of the nuclei and the electrons turn out to be relatively not too high.

At the present time the question remains unclear concerning the effect of radiation on the process of expansion of uranium which transmits the pressure to the deuterium. In order to improve the conditions of ignition it appears possible to use uranium charges of increased sizes and of a special shape (cumulation) and to introduce into the deuterium heavy elements near the initiator which might be capable of receiving the radiation pulse.

However, even with the remaining uncertainties in the question of ignition, it appears to us to be very essential to discover a system in which a single powerful pulse can initiate a nuclear detonation of an unlimited amount of matter.

APPENDIX

The possibility of carrying out a nuclear reaction is determined by the ratio between the energy emitted as radiation of electromagnetic waves and the energy of nuclear disintegration. If this ratio is less than unity, the nuclear reaction can develop. The energy radiated per second per cm^3, is equal to

$$U_r = \frac{16}{3}\frac{e^2}{\hbar c}(1+\beta)\left(\frac{e^2}{mc^2}\right)^2 v_e N^2 E. \tag{1}$$

Here v_e is the velocity of an electron, N is the number of electrons per cm^3, E is the electron energy including the rest energy, β takes into account radiation on collision between electrons, $\beta \approx 1$, while the energy summed with $\beta - 1$ corresponds to a collision of an electron with a deuteron.

The energy released in nuclear disintegrations per second per cm^3 is equal to

$$U_d = \sqrt{2}\,\sigma_c v_d N^2 \varepsilon, \tag{2}$$

where ε is the energy released in a single event of nuclear reaction, σ_c is the disintegration cross section, v_d is the deuteron velocity.

$$\frac{U_r}{U_d} = \frac{1+\beta}{120x}, \tag{3}$$

where x is related to σ_c by the expression

$$\sigma_c = x\cdot 10^{-24}\,\mathrm{cm}^2.$$

Formula (3) is obtained for energies E equal to 1/2 MeV. Such a value of E is obtained by taking into account the heating of deuterium in the front of a nuclear detonation wave (in analogy with the heating of gases in a detonation wave according to the theory of Ya. B. Zel'dovich) in the case of a total energy of a nuclear reaction 4 and its uniform distribution between all the particles (2 deuterons and 2 electrons).

Setting x equal to 1/20 (experimental data of Allen *et al.*, Phys. Rev. 1939. V. 56, P. 383) we obtain

$$\frac{U_r}{U_c} = \frac{1+\beta}{\sigma}.$$

Thus, this ratio is less than unity, and this favors the development of the nuclear reaction.

The detonation wave can be propagated over the deuterium "charge" only in the case if its dimensions are sufficiently great. This minimum size is in order of magnitude equal to the product of the velocity of sound by the time of the reaction. The latter is determined by the expression

$$\tau = \frac{\Lambda}{v_d} = \frac{1}{\sqrt{2}\,N\sigma_c v_d}.$$

the velocity of sound is

$$c \approx \frac{2}{3}v_d.$$

The critical diameter is

$$d \approx c\tau \approx \frac{3}{2\sqrt{2}\,N\sigma_c} \approx \frac{1}{2}\,\mathrm{m}. \tag{4}$$

This value may in fact turn out to be less, if the "charge" will be enclosed in a massive shell, and also due to the fact that an alternative reaction D(D,n)He^3, will be taking place which will increase the energy release and decrease the time of the reaction.

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