HEAVY STABLE PARTICLES AND COLD CATALYSIS OF NUCLEAR FUSION

By B. L. Ioffe, L. B. Okun', M. A. Shifman and M. B. Voloshin

Institute of Theoretical and Experimental Physics, Moscow*

(Received October 3, 1980)

We reanalyse critically the suggestion of using hypothetical heavy stable particles for industrial catalysis of nuclear fusion reactions at low temperatures.

PACS numbers: 28.50.Re

It is well-known that the main obstacle which blocks the way for nuclear fusion reactions of the type

$$t+d \rightarrow {}^4\mathrm{He}+n+17.6\ \mathrm{MeV}, \tag{1a}$$

$$d+d \begin{cases} \nearrow {}^3\mathrm{He}+n+3.3\ \mathrm{MeV},\ 50\% & \text{(1b)} \\ \searrow {}^3\mathrm{H}+p+4\ \mathrm{MeV},\ 50\%, & \text{(1c)} \end{cases}$$

at moderate temperatures is the Coulomb repulsion of the colliding nuclei. As it was noted by Frank [1] the repulsion can be screened by the negative muon captured by a nucleus on an atomic orbit. Sakharov and Zeldovich [2, 3] proposed to use this phenomenon for a muon catalysis of nuclear fusion. The effect was discovered experimentally by Alvarez et al. [4] in 1957. However, at that time it seemed doubtful that it could be of practical importance. Later it became clear [5, 6] that mesomolecular effects enhance the effectivity of the muon catalysis, and the possibility of its practical utilization is discussed now in the literature (see, e.g. Ref. [7]).

The effective muon-induced power cycle is difficult to realise [8, 9] because of "sticking" of muons to He nucleus and because of the short muon lifetime. It is obvious that the difficulty associated with the muon instability would disappear could one use a stable (or almost stable) heavy particle as a catalyst. Although at present one cannot insist that such particles exist, they are, nevertheless, present in some promising models, e.g. in

* Address: Institute of Theoretical and Experimental Physics, Moscow 117259, USSR.

those called technicolor scheme [10]. Moreover, from time to time reports appear in the literature claiming possible detection of heavy, relatively long-living particles (see, e.g. Ref. [11]).

In the series of recent publications [12, 13] the possibility of practical utilization of hypothetical stable particles (new leptons, hadrons, quarks and diquarks) is discussed. The most detailed discussion is given in a very interesting paper by Zweig [12].

Here we will show that the existing acceleration methods, even under the most auspicious conditions, do not allow to accumulate a minimal number of the stable particles necessary for the industrial application, and the power invested to generate such particles is not repayed. Thus, the realization of the idea of the cold nuclear fusion catalysis with the help of heavy stable particles requires either creation of new generation methods, or discovery of such particles in a "ready state" in Nature.

Let us consider the catalysis induced by a hypothetical particle X^- deprived of ordinary strong interactions with mass $M_X \gtrsim 10$ GeV. (e^+e^- annihilation experiments imply that such particles with lower masses do not exist, see also Ref. [14]). Suppose the X^- particle is placed in the deuterium or deuterium-tritium plasma. Evidently, within a time of order of the characteristic time interval between two subsequent collisions of a nucleus in the plasma the X^- particle captures a deuterium (tritium) nucleus on the Bohr orbit and, as a result, a neutral hydrogen-like system dX^- or tX^- emerges. The radius of this hydrogen-like atom is of order $(m_N\alpha)^{-1} \sim 10$ fermi and the Coulomb barrier of the nucleus is completely screened off.

Moreover, within a time of order $(n\sigma_1 v)^{-1}$ (n is the concentration of nuclei in the plasma, σ_1 is the cross section of the nuclear fusion reaction under consideration, and v is the average velocity of nuclei in the plasma) two nuclei fuse: the bound nucleus from the atom-like system, and free one from the plasma form the final helium or tritium nucleus and shake off X^- particle, which is now free again and ready to repeat the process described above with two new plasma nuclei. Thus, each X^- particle in the cold dd or dt plasma generates a chain of fusion reactions.

The chain is not endless, however, since there is finite probability for the final products of the reactions to form a "wrong" bound system, namely, $(HeX)^+$ and $(pX)^0$. When captured by He or p the X is naturally out of the game and can not play its role of a neutralizer for the deuterium and tritium Coulomb barriers.

Actually, Xp pairing is not dangerous since (Xp) bound pairs automatically turn into "active" Xd or Xt states by means of the interchange reaction of the type

$$(Xp)+d \to (Xd)+p. \tag{2}$$

Really, the binding energy of Xd is twice as large as that of Xp — the process (2) is exothermal, the energy release being about 25 keV. Moreover, the cross section of the reaction (2) is large, of order of a nuclear one. Thus, the wandering of the Xp atoms in the plasma inevitably finishes in the transmutation Xp → Xd (Xt).

On the contrary, XHe pairing is very "dangerous" — in this case nobody knows how to liberate the X particle automatically. As a matter of fact Zweig has noted [12] that the ^{3}HeX ions can be easily destroyed with the help of thermal neutrons if one uses the process

$$n+(^3\mathrm{HeX}) \rightarrow {}^3\mathrm{H}+\mathrm{p}+\mathrm{X}. \tag{3}$$

This process has a very large cross section, $5 \cdot 10^3$ barn. The small energy release in the reaction $n+{}^3\mathrm{He} \rightarrow {}^3\mathrm{H}+\mathrm{p}+0.7$ MeV results in the fact that the X particle in the process (3) is practically always "stuck" either with tritium (predominantly) or with hydrogen. Both alternatives are favourable. Unfortunately, the neutron burning proposed by Zweig is impossible to realize in practice. The matter is that the required neutron flux turns out to be enormous. As we shall see below the time for the neutron burning must be certainly less than 10^{-4} sec. With the cross section $\sigma \sim 10^{-20}\,\mathrm{cm}^2$ this implies that the neutron flux must be larger than 10^{24} neutrons/cm^2 sec. Let us notice, that the maximal flux in existing high-flux reactors is of order $10^{15}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.

Summarizing, it is the HeX pairing that blocks the catalytic activity of the X particle. The probability P_s for the formation of the $(\mathrm{HeX})^+$ ion is quite analogous to that of the $(\mathrm{He}\,\mu)^+$ ion; the latter was estimated by Zeldovich [3] by means of the so called "shake off" method [15]. The approximate expression for P_s is

$$P_s \simeq \left(1+\left(\frac{qa}{2}\right)^2\right)^{-4} \simeq \left(1+\left(\frac{v_{\mathrm{He}}/c}{4\alpha}\right)^2\right)^{-4}, \tag{4}$$

where v_{He} is the velocity of the He nucleus produced in the fusion reaction, $a = (Z\alpha m_{\mathrm{He}})^{-1}$ is the Bohr radius of the HeX system ($m_{\mathrm{He}} \ll m_X$).

For reaction (1a) $v_{\mathrm{He}}/c = 4.3 \cdot 10^{-2}$ and $P_s \simeq 10^{-2}$. For reaction (1b) $P_s \simeq 0.2$. And, finally, for reaction (1c) the probability of Xt sticking is of order $3 \cdot 10^{-3}$ while that of Xp sticking is of order 10^{-6}. Thus, before the X particle is lost because of the ^{4}HeX pairing, it induces $n = P_s^{-1} \simeq 100$ reactions (1a) with the total energy release $n \cdot 17.4$ MeV $\simeq 1700$ MeV. In case of the pure deuterium plasma (reactions (1b), (1c)) the X^- particle induces half a dozen of fusion acts, before it is captured by ^{3}He.

We see that dt plasma is more preferable than pure dd one. It is the dt plasma that we shall consider below.

Two comments are in order here. First, the numerical estimates obtained above for dd plasma are rather rough since at small values of the parameter $v/4c\alpha$ the accuracy of Eq. (4) is low. More accurate calculations would be of interest. Second, under industrial applications the energy output can be easily increased by a factor of 30 (as compared to the numbers given above) if one utilizes the neutrons produced in (1) by capturing them in uranium blankets surrounding the reaction zone. In further discussions one may keep this factor in mind. It will become clear a bit later, however, that allowing for such a possibility does not affect our conclusions.

The loss of the X particles due to ^{4}HeX sticking and the necessity for their regeneration is one of the main problems, the "bottle-neck", of the X catalysis. Really, if one attempts to destroy all the stuck ^{4}HeX pairs by exposing the plasma in an electron or gamma-ray beam one immediately discovers that the lion's share of the beam energy is spent not on the X liberation, but on the warming-up the plasma itself. As a result, long before the X particles are ionized, the plasma becomes hot, and the ordinary "hot" thermonuclear synthesis starts. Evidently, this way excludes any advantages or benefits due to the presence of the X catalyst in the plasma. As a possible way out one can propose a separation of (^{4}HeX) bound systems from the plasma prior to the X regeneration. Either physical or chemical methods of enrichment can be used, for example, a high-frequency centrifuge. Evidently, the time interval T needed for the enrichment and regeneration, is a most crucial parameter. As we will demonstrate below, the problem is not only of a technological but also of a principal character. It seems safe to say that T can not be much lower than $\sim 10^{-3}$ sec irrespectively of what physical or chemical method is applied. With this number in mind let us make an estimate of the expediency of the X catalysis. (The interval T includes the time needed for the enrichment of the plasma by ^{4}HeX, ionization of the X particles and their return into the reaction zone. In all the equations below we leave T unspecified while in numerical estimates we substitute $T = 10^{-3}$ sec).

We will base further consideration on two parameters which may serve as criterions for the expediency of the X catalysis:

(*i*) The absolute power capacity of a power station with the given number of the X particles;

(*ii*) The ratio of the energy output to the energy spent to produce the X particles by accelerators.

The power capacity W is evidently given by the relation

$$W = nQN/T,$$

where N is the number of the X particles in the apparatus, Q is the average energy release per act of the catalysis and, finally, n is the number of the reactions catalysed by a particle prior to its capture by a ^{4}He nucleus (in other words n is the number of the fusion acts per active period). The regeneration time T was defined above.

Substituting $n = 100$, $Q = 10$ MeV, $T = 10^{-3}$ sec one obtains

$$W = 10^3\ \text{GeV} \cdot N/\text{sec} = 1.6 \cdot 10^{-16}\ N\ \text{GW}. \tag{5}$$

A power facility can be considered as economically expedient if its power capacity is larger than one of the order of 1 GW. As it immediately follows from Eq. (5) to provide such a capacity one needs at least 10^{16} X particles. Let us note, that 10^{20} X particles would be enough to meet all power requirements of the mankind. (A reservation is in order here: the above numbers rely heavily on the estimate $T = 10^{-3}$ sec which can be considered only as an uneducated guess, nothing more).

The total energy release per each X particle during the interval t of the facility operation, is equal to

$$A = nQc, \tag{6}$$

where $c = t/T$ is the number of the regeneration cycles. If $t = 1$ year ($n = 100$, $Q = 10$ MeV, $T = 10^{-3}$ sec) then

$$A = 3 \cdot 10^{10}\ \text{GeV}. \tag{7}$$

Let us compare these results, $N \sim 10^{16}$ particles and $A \sim 10^{10}$ GeV, with the potentialities of modern accelerators. We start with storage rings and consider the most favourable lepton case, i.e. assume the X particle to be a lepton. The optimal way to produce such a lepton is to collect the decay products of the Z boson formed resonantly in the direct channel of the e^+e^- annihilation reaction, $e^+e^- \to Z^0 \to X^+X^-$. If the partial width for the decay $Z^0 \to X^+X^-$ is of order of 0.03 of the total Z^0 width, then $\sigma(e^+e^- \to Z^0 \to X^+X^-) \simeq 10^{-33}$ cm^2. The number of the generated X particles is determined not only by the cross section, but by the luminosity of the storage rings L as well,

$$N = \sigma L t, \tag{8}$$

where t is the period of operation. One can easily convince oneself that even with such a large cross section producing of $N = 10^{16}$ X particles during a year requires $L = 10^{41}$ cm^{-2} sec^{-1}. Let us recall that the project of the LEP storage rings envisages $L \lesssim 10^{33}$ cm^{-2} sec^{-1}.

The power expenditure per each X particle in the storage rings would constitute

$$A_{\mathrm{SR}} = W_{\mathrm{SR}}/\sigma L, \tag{9}$$

where W_{SR} is the power consumed by the collider. For LEP it is within 10–100 MW. Substituting $\sigma = 10^{-33}$ cm^{-2}, $L = 10^{33}$ cm^{-2} sec^{-1} we find that at LEP

$$A_{\mathrm{SR}} \gtrsim 10^7\ J = 6 \cdot 10^{16}\ \text{GeV}. \tag{10}$$

Comparing Eqs. (7), (10) immediately shows that modern colliders do not meet the case by many orders of magnitude.

The situation is not better for stationary target accelerators. In this case

$$N = BIt. \tag{11}$$

Here $B = \sigma_X/\sigma_{tot}$, where σ_X is the cross section for X particle production and σ_{tot} stands for the total proton-target cross section; I is the accelerator intensity. For CERN and Fermilab supersynchrotrons, with the acceleration energy E $\sim$ 500 GeV, $I = 10^{13}$ protons/sec.

To estimate the ratio B one can invoke experimental data [17] on μ pair production in pN collisions. Acording to Ref. [17] at $E_p = 400$ GeV the cross section for $\mu^+\mu^-$ pairs with mass $\sim$10 GeV amounts to $\sigma(\mathrm{pN} \to \mu^+\mu^- + \text{hadrons}) \sim 10^{-37}$ cm^2. Extrapolating the curves we come to a conclusion that at $E_p \gtrsim 500$ GeV and in the interesting mass range $M(X^+X^-) > 20$ GeV

$$\sigma(\mathrm{pN} \to X^+X^- + \text{hadrons}) \lesssim 10^{-38}\ \text{cm}^2.$$

Since $\sigma_{tot}(\mathrm{pN}) \simeq 4 \cdot 10^{-26}$ cm^2 the ratio B turns out to be $B \lesssim 10^{-13}$. As a result, it would take of order of 10^7 years of operation for a modern accelerator to produce the needed amount (10^{15}) of X particles. Even the most advanced large-current facilities under discussion now with particle current $I \approx 300$ mA $= 2 \cdot 10^{18}$ protons/sec would not save the situation. (Note that the projects of such facilities thus far do not go far beyond the energy $E_p \sim 1$ GeV).

So much about the first criterion ($N \sim 10^{15}$) as applied to a stationary target machine. Now, as to the second criterion. It does not turn out favourable either. The power expenditure for generation of each X particle can be estimated by using the following equation:

$$A_{acc} = E_p/B, \tag{12}$$

where E_p is the proton beam energy and the quantity B is the ratio defined above. Taking $E_p = 500$ GeV and $B = 2 \cdot 10^{-13}$ we find

$$A_{acc} = 2 \cdot 10^{15}\ \text{GeV}. \tag{13}$$

It is important that the latter number can not be reduced considerably since it is determined not by technology or acceleration technique, but by the ratio of two constants "fixed by nature": the threshold energy and the X production cross section. Actually, A_{acc} is even larger since we have not taken yet into account various efficiencies: of the accelerator and power station, due to the leakage of X particles and so on. Thus, $A_{acc} \sim 10^{16}$ GeV is surely not an overestimate. Comparing this number with Eq. (6) one sees that the X catalysis becomes energetically advantageous if only c, the number of regeneration cycles, is larger than 10^{16}. It implies, in turn, that the relative share of the lost X particles per each regeneration cycle must be less than 10^{-16}. Both the enormous number of regeneration cycles and the extremely small loss factor do not seem to be realizable. As a matter of fact the necessary number of regeneration cycles might be lowered, if colliding beams of new type, with small energy losses, are realized, say, the linear colliding beams with energy recuperation. Such a machine would combine the virtues of a collider (a large value of B in the Z resonance, a low threshold: $2m_X$ instead of $2m_X^2/m_p$) with those of a stationary target accelerator (absence of synchrotron losses, etc.) However, even with such machines the possibility to obtain the required number of X at acceptable price is highly questionable.

The situation would look more optimistic if one happened to find a geological "deposit" of the X particles. Estimates based on the hot Universe model (analogous to those made earlier [18] for quarks) show that mean concentration of the X particles in the surrounding matter must be rather high. In the normal matter the X particles would be bound to form peculiar "queer" atoms. The search for such "queer" atoms has been performed repeatedly [19] with the stable negative result. It is possible, however, that the X particles are still present in the normal matter, but have not been found due to the very large mass of the corresponding "queer" atoms, far above the investigated mass range. In this case new search would be of great importance. We would like to mention also one more alternative. The particles might not be absolutely stable. Supposing that at distances of order of the Plank length the synthesis of all interactions takes place, the X particle must decay into normal hadrons and/or leptons, its life time being of order

$$\tau_X \sim m_G^4/\alpha^2 m_X^5,$$

where m_G is the mass of an intermediate boson which couples the X matter and the normal one. Of course, if one takes (following Ref. [20]) $m_G \sim 10^{15}$ GeV, then τ_X is larger than the life time of the Universe, $\tau_X \sim 10^{20}$ years, so that the X matter is practically stable. In alternative models (see e.g. Ref. [10]) the Unification scale may be much smaller, however. In particular, the estimates

$$m_G \sim 10^{11}\ \text{GeV}, \qquad \tau_X \sim 10^4\ \text{years}$$

do not seem unreasonable. Thus, apriori one can not exclude the existance of an appropriate interaction which would destroy the X particles with such a rate. Naturally, in this case no relic X particles would survive.

In spite of the pessimistic colouring of our estimates it is doubtless that the hypothesis of stable or almost stable heavy particles deserves further theoretical and experimental investigations. It is difficult to forsee now all possible applications of such particles. Some of them may turn out to be vital. Moreover, the problems discussed above may be solved and the difficulties circumvented in this or that way. It is quite possible that the new stable particles fall in the interval accessible for the accelerators under construction.

We are grateful to S. S. Gershtein, Y. M. Shabelsky, V. A. Khoze and Yu. V. Petrov for valuable discussions.

REFERENCES

[1] F. C. Frank, *Nature* **160**, 525 (1947).
[2] Ya. B. Zeldovich, A. D. Sakharov, *Zh. Eksp. Teor. Fiz.* **32**, 947 (1957).
[3] Ya. B. Zeldovich, *DAN SSSR* **95**, 454 (1954).
[4] L. W. Alvarez et al., *Phys. Rev.* **105**, 1127 (1957).
[5] E. Vesman, *Zh. Eksp. Teor. Fiz. Pisma Red.* **5**, 113 (1967).
[6] S. S. Gershtein, L. I. Ponomarëv, in *Muon Physics*. Ed. by V. Hughes, C. S. Wu, Academic Press 1975, v. III, p. 141.
[7] Yu. V. Petrov in *High-Energy Physics*, Proc. 14 LNPI Winter School of Physics, Leningrad 1979, p. 139.
[8] J. D. Jackson, *Phys. Rev.* **106**, 330 (1957).
[9] Ya. B. Zeldovich, *Zh. Eksp. Teor. Fiz.* **33**, 310 (1957).
[10] L. Susskind, *Phys. Rev.* **D20**, 2619 (1979); S. Dimopoulos, L. Susskind, *Nucl. Phys.* **B155**, 237 (1979).
[11] J. A. Goodman et al., *Phys. Rev.* **D19**, 2572 (1979).
[12] G. Zweig, *Science* **201**, 973 (1978).
[13] R. Cahn, *Phys, Rev. Lett.* **40**, 80 (1978); P. Freund, C. Hill, *Nature* **276**, 250 (1978).
[14] L. G. Landsberg, in *Problems of Nuclear and High-Energy Physics*, Nauka, Moscow 1975, p. 43.
[15] A. B. Migdal, *Zh. Eksp. Teor. Fiz.* **9**, 1163 (1939).
[16] J. Le Duff, in Proc. LEP Summer Study, CERN 79-01, v.I, p. 201, Geneva 1979.
[17] J. K. Yoh et al., *Phys. Rev. Lett.* **41**, 684 (1978).
[18] Ya. B. Zeldovich, L. B. Okun, S. B. Pikelner, *Usp. Fiz. Nauk* **87**, 115 (1965).
[19] G. M. Kukavadze et al., *Zh. Eksp. Teor. Fiz.* **47**, 1777 (1964); T. Alvager, R. A. Nauman, *Phys. Lett.* **24B**, 647 (1967); P. F. Smith, J. Bennett, *Nucl. Phys.* **B149**, 525 (1979).
[20] A. Buras et al., *Nucl. Phys.* **B135**, 66 (1978); Proc. Seminar on the Proton Stability, ed. by D. Cline, Univ. Wisconsin 1978.