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PERSPECTIVE OF A NEW PATH TO CONTROLLED NUCLEAR FUSION

by

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Summary

It could be summarized that "It is not impossible to build a μ CF reactor". It seems that we have clearly passed the threshold "Impossible". By an active research and development it will be possible to build one. There are many things we have to do, not only in technical details but also in fundamental physics. The μ CF physics is very interesting as science and worth pursuing. Currently many physicists are involved in this research, including a group under Prof. Lopes. For experimental study we need muons. At present there are four accelerators in the world doing muon physics. They are LAMPF in United States, SIN in Europe, KEK in Japan, and Triumf in Canada. If an accelerator were built in Brazil, the world-wide research will be more well-balanced. By international collaborations we hope to succeed in constructing a μ CF reactor.

1. Introduction

In this article a new method of attaining controlled nuclear fusion will be described which is called muon catalyzed fusion (μ CF). This utilizes artificially produced particles, i. e. muons, as catalyzers of fusion reaction. The μ CF recently received much attention. In Rio de Janeiro, Professor Leite Lopes and his group at the Centro Brasileiro de Pesquisas Fisicas are actively studying the subject. In Japan a group at the University of Tokyo is doing experimental research on this and in many other places in the world people are working on this problem. So let us see how the present status of research on this μ CF is and the prospect of its future.

2. Energy Resources

Before starting the issue, some data on the world energy problem will be in order. Man is obtaining energy mostly by burning fuels but natural resources are limited. Currently we are using about 0.3 Q of energy every year where Q is a very large unit of energy $\doteqdot 10^{21}$ joule. The amount of energy from petroleum on earth is estimated to be about 30Q, although new oil wells may be found. Coal is inconvenient to use and is not much used now, but the coal energy on earth is about 100 Q. It is also estimated that man will consume 70 Q of energy in the next 100 years. So if we rely on these petrified fuels only, we shall run out of them shortly.

Nuclear energy is another energy source. Currently it is obtained by nuclear fission. That is, when a certain type of uranium isotope is hit by a neutron, it splits into two releasing a great amount of energy. Uranium is abundant on earth but rich mines are scarce. The estimation of the total amount of energy obtainable from nuclear fission turns out to be about 300Q. So after hundreds of years man will face another energy crisis.

Nuclear fusion is opposite to nuclear fission. Two light nuclei, e. g., two heavy protons (heavy proton = deuteron, abbreviated by d) come close to each other, they fuse into one and also release energy:

$$d + d \rightarrow {}^{3}\mathrm{He} + n + 3.27\ \mathrm{MeV}. \tag{1}$$

A more favorable fusion reaction is

$$d + t \rightarrow \alpha + n + 17.6\ \mathrm{MeV}, \tag{2}$$

where t (triton) is another isotope of the proton.

In the case of fusion, the fuel is almost infinite. Deuteron is contained in water. The total heavy water in ocean can produce 10^{10} Q of fusion energy. Thus if we succeed in obtaining controlled fusion energy the energy problem will be solved. Energy will become available almost free. For this reason the controlled release of nuclear fusion energy is essential for our future.

We have not yet succeeded in it. The difficulty in making hydrogen nuclei to fuse is that both are positively charged and the electrostatic repulsion prevents them to come near to each other. A way to overcome this repulsion is to make hydrogens very energetic, i. e., to keep hydrogens at an extremely high temperature. In order to confine the material at this extreme state we use an electromagnetic field produced by an apparatus called tokamak or use high pressure in explosion of ammunition or irradiate by lasers. At present none of these methods are successful in confining the hot plasma such that fusion reaction takes place in it.

3. Muon Catalyzed Fusion

Instead of high temperature, muons can be utilized to speed up the fusion reaction. The idea is as follows.

The muon is a particle that does not exist in nature, but can be artificially produced by an accelerator. The negatively charged muon, μ^- , is almost identical to the electron except that it is heavier. The muon is about 200 times heavier than the electron. An electron, being negatively charged, is attracted by a hydrogen nucleus (p, d, or t) and forms a hydrogen atom. Or an electron and two hydrogen nuclei form a hydrogen molecule ion H_2^+. Quite similarly, a negative muon makes a mu-atom, μ p, μ d, or μ t, and a mu-molecule μdt, etc.. The difference is that mu-atom or mu-molecule is much smaller that the ordinary atom or molecule. The size being inversely proportional to the mass, the mu-molecule is 1/200 in size compared with the ordinary hydrogen molecule. In μ dt, the two nuclei d and t are close to each other and in a short time they make a fusion reaction

$$\mu\,dt \rightarrow \alpha + n + \mu . \qquad (3)$$

The muon is kicked out and with other nuclei forms another μ dt molecule. In this way we have a chain cycle of reactions. A muon is sent into deuterium-tritium mixture. A μ dt molecule is formed. Then the fusion reaction takes place and the liberated muon forms another molecule. In this cycle muon is not consumed. It acts as a catalyzer of the fusion reaction. For this cycle, high temperature or high pressure is not necessary. The reaction proceeds in room temperature and pressure. This cycle was predicted 40 years ago and the chain of reactions was actually observed 30 years ago.

This is not the end of the story. The muon is short-lived and cannot be used as a permanent catalyzer. After $2X10^{-6}$ sec it disintegrates into an electron and neutrinos. So during this short lifetime a muon must make many fusion cycles for it to be a useful catalyzer. It turned out that one cycle takes place in a fairly short period and that repeated reactions did happen. Our fusion reactor will consist of two parts. One is a muon producing machine that constantly supplies muons. The other is a furnace that burns hydrogen by muon catalysis. It requires at least 100 MeV of energy to make one muon, and in one fusion, i. e., in one cycle, 17.6 MeV is produced. So if one muon can make more than six cycles before it is dead, in principle we can get energy from the reactor. In order to make muons the usual way is to bombard nuclear target by accelerated particles and produce pions. Pions then turn into muons. There is loss of energy everywhere. In accelerating particles only a fraction of input energy can be converted to particle energy. There is a loss in hitting the nuclear target, not all pions or muons can be collected, etc.. So actually six cycles are quite insufficient for an actual reactor to work.

A serious limitation on this fusion cycle was found, that is, sticking of a muon to α particle. By the reaction (3) muon is kicked out but in rare cases it is bound to α and forms a $(\mu\alpha)^+$:

$$\mu d\, t \rightarrow (\mu\alpha)^+ + n. \tag{4}$$

The probability of this occurrence is called sticking probability. This bound muon is no longer used as a catalyzer. The sticking probability in the dt reaction was estimated to be 1 %. This sets an upper limit of the number of fusion cycles. Even if one cycle goes very fast, in one hundred times of cycling the muon is bound to α and becomes inactive. So cycles per muon cannot be more than one hundred. One hundred was supposed to be too small for a reactor. People thought if the cycles were three hundreds or more it would not be impossible to build and operate a μ CF reactor, but < 100 is less than insufficient. Many people lost interest in this problem. That was the situation of μ CF in the late 1950's.

4. Present Status.

Investigations on μ CF went on and were accelerated in recent years. Behaviors of muons in hydrogen have been fairly well studied. It was found that the fusion cycling does occur reasonably fast. When a muon is sent into deuterium-tritium mixture, it is captured by d or t and forms a μd or μ t atom. This takes place almost instantaneously compared with the muon lifetime. Then the μ t atom collides with d and form a μ dt molecule. This formation is slow, but a mechanism of resonant formation of μ dt molecule was discovered and, under a favorable condition, i. e., with certain concentration of D - T, reasonable temperature, etc., the molecular formation takes place more than 1000 times in a muon lifetime. After the molecule is formed, d and t fuse almost instantly. Thus the limitation comes mostly from sticking.

We know the rate of molecular formation, etc., so from the number of fusion reactions one can calculate the sticking probability experimentally. This was done in Los Alamos National Laboratory, U. S. A.. At low hydrogen density they obtained 1.1 % for sticking probability. However, at higher density, the probability was 0.6 %, and, at even higher density it decreased to 0.35 %. The decrease of sticking probability with increasing hydrogen density can be explained as follows. The bound $(\mu\alpha)^+$ is traveling fast and when it collides with other molecule, the muon is often stripped. This is an activation of dead catalyzer. The observed sticking probability is the effective probability after this reactivation. In another experiment at Swiss Institute of Nuclear Research, the sticking probability was measured to be 0.5 - 0.45 % even at low density. Results are not consistent to each other.

A group at the Meson Science Laboratory, University of Tokyo, tried to observe the sticking more directly. When $(\mu\alpha)^+$ is formed, some are in excited states and emit an X-ray of a definite energy. They tried to observe this X-ray but obtained only a few. In terms of the sticking probability, it is 0.12 - 0.2 % and is very small. They are repeating this experiment for confirmation. There is also a plan to catch $(\mu\alpha)^+$ ion directly.

Experimental results of $\mu\alpha$ sticking are not consistent to each other, but the value of the probability which was once supposed to be 1 % is probably incorrect. It must be much smaller and may be very small. The inconsistency among experimental groups may be due to some misunderstanding of muon processes.

5. Prospect

If the sticking probability is 0.3 %, this means that a muon can make 300 cycles of fusion reaction before it becomes inactive. "300" is the number which was supposed to be "not impossible to build a μ CF reactor". 6 cycles is the point of energy balance and 300 is 50 times more. If the efficiency of the machine is 2 %, i. e., if 2 % of the output energy can be turned into muon production, the reactor runs. By physical and technical research and development it will be possible to do this.

Research and development should be directed in many ways. First, there should be more fusion cycles per muon. This can be achieved by reactivating the dead muon bound to α . By choosing favorable conditions, stripping of muon from $(\mu\alpha)^+$ may be encouraged. Or more positively, we may collect $(\mu\alpha)^+$ ions and irradiate them to liberate bound muons. Or there may be a drastic way of increasing fusion cycle. We have not yet completely understood the muon process.

Second, invention of an efficient machine to produce muons. Muons are born from pions, so a large amount of pions should be produced. One way is to build a pion laser. Pion is in many respects similar to the light. Laser is an apparatus to produce strong light. In a similar way we may construct a

PASER (Pion Amplification by Stimulated Emission of Radiation) that creates a strong beam of pions.

Third, hybrid reactor. Pions are produced by hitting nuclei by accelerated particles. Some of the particles miss to hit the target. Such particles are used to bombard uranium. Ordinary uranium is inactive against fission, but by bombardment some become active. Also fast neutrons obtained by fusion (3) can be used to activate uranium. We operate fission reactor beside μ CF reactor and this will greatly increase the efficiency.