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THE PION (MUON) ENERGY PRODUCTION COST IN MUON CATALYZED FUSION

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1 What muons can do (to the history of the question)

1947. Powell with his co-workers discovered muons [1] - the particles with the same characteristics as electrons, except their masses. The muon mass is by 207 times greater than the electron one.

Frank F.C. was the first who made a hypothesis to use negative muons to catalyze light nuclear reactions with the aim to get the new energy source [2].

The idea of the muon catalysis mechanism is simple enough. When the negative muon comes to rest in hydrogen environment, it may be captured into a stable orbit around the light nucleus and a μ-mesonic hydrogen atom is formed (p_μ, d_μ, t_μ). The formation takes place during the shorter time if to compare with the μ-meson lifetime. The Borh's radius of a μ-mesoatom is by 207 times less than the radius of the normal hydrogen atom $a = \hbar/me^2$, where m_e should be changed to $m_\mu = 207\ m_e$, m_e - electron mass. Due to its neutrality and small size the μ-mesoatom can come close to another nucleus and form a bound molecule consisting of two hydrogen nuclei and a μ^- meson. The larger meson mass compared to the electronic mass means that the bound system, for instance $(p + d + \mu^-)$, will be much smaller than electronic orbital distances. The two hydrogen nuclei in their vibrational motion penetrate the Coulomb barrier and come within a nuclear interaction distance of each other. Then they have a certain probability of forming a compound nuclear system which subsequently de-excites with the energy liberation in the form of kinetic energy of particles or radiation. The net result is the occurrence of a nuclear reaction through the intermediary of a μ^- meson. The μ^- meson being set free, is unaffected in the process and ready to form the new mesoatom, i.e. to repeat the full cycle from the beginning.

If mesoatom connects with nucleus which has $Z > 1$, then the μ^- meson may be captured to the orbit of this nucleus forming the new mesoatom, for instance He_μ, Li_μ. But these bound systems are not electroneutral and another nuclei, even proton, can not penetrate the Coulomb barrier to zero separation where they may undergo a nuclear reaction. These muons will not take part in the muon catalysis fusion (μCF) process, they will decay by natural way ("dead-end" processes).

So, let us consider the main steps of the μCF study — what muons can do.

1948. Sakharov [3] considered theoretically the nuclear reaction catalyzed by μ^- mesons in liquid deuterium. He estimated the lifetime of the dd_μ molecule. It was $\sim 10^{11}$ sec i.e. $\sim 10^5$ times less than lifetime of the muon (2.2210^{-6} sec). It means that a single muon can initiate a great number of nuclear fusion cycles. The energy liberated in each cycle totally may grow up to a significant value.

1954. Zeldovich [4] came to the conclusion on the possibility of nuclear fusion of hydrogen isotopes (p, d, t) by μ^- mesons. These estimates showed that the probability for muon to be captured in flight was negligibly small, the mesomolecule formation was always finished by fusion of their nuclei, the resonance mechanism could take place and it would lead to the larger probability of mesomolecules formation.

1957. The experimental confirmation of the catalysis of nuclear reactions between hydrogen isotopes by μ^- mesons was obtained. It was found at Berkley by Alvarez et. all [5] that incident negative muons in a hydrogen bubble chamber containing both light hydrogen and deuterium are working as a catalyst for the nuclear reaction

$$p + d + \mu^- \rightarrow He^3 + \mu^- + 5.4\ MeV$$

with the μ^- meson carrying off the available energy. They observed some cases in which μ^- meson coming to rest in the hydrogen caused a secondary negative particle of 1.7 cm range which in its turn decayed in emitting an electron. In some of these events there was a large gap between the last bubble of the primary muon track and the first one of the secondary muon track. These real gaps were thought to be the distance covered by the small neutral mesonic atom. The energy of the "rejuvenated" μ^- meson was 5.4 MeV, i.e. nearly the mass difference between H+D and He^3.

Cristi et. all [6] observed that the size of the gap became smaller with increasing of the deuterium concentration in liquid hydrogen. They found the event where one muon produced reactions of nuclear fusion twice.

1957. Jakson [7] discussed in detail the mechanism whereby μ^- mesons served as catalysts for reactions between hydrogen isotopes. He also briefly considered the question of liberation of useful power amounts by the μ^- mesons. The actual rate of the energy release by the μ^- mesons was limited by the time (10^{-8} sec) spent by the muon between the breakup of one molecule and the formation of another and loss of muons in "dead-end" processes. These governing factors made the practical power production not reasonable.

After this work the interest to μCF problem reduced. It was clear that the straight and fast solution of μCF problem in practice was absent.

1960. Zeldovich and Gerstein published review [8] on the μCF problems where they considered in detail the nuclear fusion reactions in cold hydrogen and, thus, stimulated the further activity in this field.

1962. Dzhelepov et. all [9] started experiments to investigate the muon interactions in gaseous hydrogen mixture.

1977. Gersthein and Ponomarev [10] showed that due to the existence of a weekly bound state of molecule dt_μ, one μ^- meson in a mixture of deuterium and tritium could catalyze $\simeq 10^2$ of the fusion reactions forming helium and ejecting neutron and the energy of 17.6 MeV. The sum energy released by these reactions would be $\simeq 2\ GeV$. The interest to the μCF problem grew up again.

1978. Vinitsky, Ponomarev et. all [11] performed the theoretical investigation of the resonance formation of hydrogen muonic molecules dd_μ and dt_μ based on the new perturbation theory for calculation on the binding energy and wave functions of a three-body system with Coulomb interaction. Highly excited states with small binding energies were found in the dd_μ and dt_μ molecules. The presence of these levels leads to the resonance formation of muonic molecules with the value of rates which signifies that a μ^- meson can catalyze $\simeq 10^2$ reactions of synthesis of the deuterium and tritium nuclei.

1980. Dzhelepov group [12] started to investigate experimentally the fusion of deuterium and tritium nuclei via the intermediative muonic molecule state. Several runs were done with different density and temperature of the D + T mixture as well as tritium concentration. Measurement of the neutron yield showed the rate of muon transfer from deuterium to tritium and the lower limit of the formation rate of dt_μ molecules.

1980. Petrov [13] suggested an extremely new idea how to produce the energy. The idea was to combine nuclear fusion with the uranium-238 reactor. In such reactor the energy obtained from the synthesis reactions of the deuterium and tritium should be added with the energy from the fission of uranium-238 and forming plutonium-239 due to neutrons from the fusion reactions. The sum energy liberated in this reactor gave a positive economic gain. Further we come back to this question.

1983. Ponomarev [14] in his review noted that a visible progress achieved in μCF became possible due to international cooperation of physicists from many centers. He also stressed the promising perspective of Petrov's idea to produce energy by combining μCF and fast neutron reactor.

1983. Jones et. all [15] reported on the new experiments with deuterium-tritium mixture at high density in Los-Alamos Laboratory. The D-T mixture was exposed to pressure up to 1000 atm and at temperature of 100-600 K. The dependence of the rate fusion reactions on the temperature was observed in agreement with [12].

1986. Jones et. al [16] reported on the new unexpected target-density effects both in dt_μ molecular formation rate and the effective sticking probability. They registered 150 fusion reactions induced by one muon in D-T mixture at the density $\rho = 1.3\ \rho_o$ where ρ_o was the density of the liquid hydrogen ($4.2510^{22}\ atom/cm^3$). At the same time the sticking of μ^- mesons to helium nuclei ("dead-end reactions") decreased from 1% at $\rho = \rho_o$ to 0.3% at $\rho = 1.3\ \rho_o$. It was predicted to achieve $\simeq 300$ μCF reactions at the density of the D-T mixture at 2.3 ρ_o.

1986. Jones [17] wrote about the positive achievements in μCF investigations during 30 years . He generalized the main requirements to the economically fruitful project to generate the useful energy by μCF reactions. He stressed that it was necessary to create the conditions when one muon can initiate hundreds of nuclear fusion reactions and the quantity of energy needed to produce one muon should be less than $\simeq 10\ GeV$. The technical problems should be solved also and the main of them was safety.

There were years of the highest interest to the μCF problem.

1987. The new special journal "Muon Catalyzed Fusion" was issued. It publishes the proceedings of conferences and results of investigations in this field.

Still the problem to join μCF with nuclear reactor as a reliable and fruitful method to produce energy, is important. Muon catalisator placed into uranium-238 or torium-232 blankets could supply humanity with energy for a long period of time since natural resources of uranium-238 and torium-232 are much greater than uranium-235.

Petrov's idea was encouraged by Takahashi's group [18]. Petrov and Sakhanovsky [19] proposed a model of a set-up to calculate the muon efficiency for it. There were approximate sizes of the convertor and synthezator in this model for nuclear reactor with μCF reactions. The vessel for synthezator was 19 m long, the radius for D-T mixture — 10 cm and its volume was 0.64 m^3. The convertor sizes were: decay length for π mesons 40 m, the radius — 20 cm, the volume — 5 m^3. The magnetic solenoid and magnetic mirrors were expected to keep $\pi(\mu)$ mesons on the appropriate trajectories.

Obviously it was not a real project but still this model allowed to estimate what kind of work should be done to find out the optimal decision.

To get a large number of fast neutrons from μCF reactions is a strong competing process to the electronuclear breeding [20].

2 The energy cost of muons

Muons are the product of the pions decay. The pions are produced at collisions of nucleons or nuclei at high energies. As μCF reactions require slow negative muons, then pions should be generated at relatively moderate energies of the beam particles. At energy of 1 $GeV/nucleon$ the π^- mesons are mostly produced in neutron-neutron interactions. For the minimum cost of the pion production the primary beam and the target should be neutron-rich (D, T, Li, Be,...).

The problem of the minimum energy cost of the pion production seems not so hard. It is just to measure the yield, momentum and angular distributions of pions in different collisions and estimate the energy expenditure for the negative pion production. Till the present moment the estimations were performed only by Monte-Carlo calculations on the base of some theoretical model and experimental data on the cross sections. There was no direct experimental information on this point.

Let us consider briefly some results of these calculations where the main goal was to obtain the lowest energy cost of the π^- mesons production.

1. Bertin et. all [21] presented the result of calculations on the energy expenditure to produce pions and muons for the muon catalyzed fusion. To identify the optimal experimental conditions they calculated the production rate of pions under different configurations of targets and particle beams.

The simplest and effective way of using the negative pions is to produce them directly within the deuterium-tritium target, where the muons from pion decay are stopped and interact. The lowest costs were obtained for the target more than about 3 m in diameter for the neutron beam.

The system of this size would require a tremendous quantity of deuterium and tritium. If to take into account that the formation rate of dt_μ molecules increases with the density of D-T mixture as it was shown by Los-Alamos group [15-17], then due to technical reasons this system is evident not to be realistic.

The high density of the target is more favorable for the pion production and nuclei fusion processes but for the conversion process of pions into muons, the low density of the target is more preferable because the absorption of π^- mesons by the target becomes less.

Bertin et.all [21] considered also a more conventional attitude to form muons from the decay of the intermediate pion beam and stop the muons themselves within the D-T-mixture. In this case (ideally, if all the produced muons were collected) the lowest energy cost was about 3 GeV.

In both cases the large quantity of tritium made this scheme not attractive and dangerous. In the case of unhermeticality of the target, the ecological catastrophe becomes inevitable.

2. Petrov and Shabelsky [22] considered the energy cost for pion production for interactions of d-, t- nuclei beams with thick prolonged targets of Li and Be. The calculations were performed for the target of 2 and 6 m long and with diameter of 8 and 24 cm and for the beam energy of 1 $GeV/nucleon$. They found that the energies needed to produce one π^- meson were: for d+Be — 5.6 GeV, d+Li — 5.5 GeV, and for t+Be — 4.6 GeV, t+Li — 4.4 GeV. They also founded that energy and angular distributions of pions weakly depend on the target size.

3. Kazarnovsky et. al [23] calculated the π^- energy cost for the d+Be reactions at 1 $GeV/nucleon$ using one more independent method. The beryllium target was 2 m long and the diameter — 8 and 4 cm. They found the value 6 GeV.

As it was mentioned above, there was not any other experimental information on this subject.

3 Experimental measurement of the pion yield

In 1987 prof. Ponomarev proposed for our group to investigate the π^- meson production in beryllium and carbon extended targets by means of the 2-meter propane bubble chamber in magnetic field exposed to beams of light relativistic nuclei from the Dubna synchrophasotron. Experimental estimation of the energy cost for one pion production as function on energy and sort of beam-particle, was one of the main goal of this activity.

To complete this program an extended cylinder target was placed along the beam inside the sensitive volume of the propane bubble chamber. The corresponding developments in reconstruction program and selection criteria were done. The carbon extended target was made of graphite with a cylinder form (length 30 cm, diameter 10 cm and density 1.73 g/cm^3). For the beryllium target the corresponding values were 28 cm, 6 cm and 1.848 g/cm^3. The results of our measurements are published in [24-27].

The influence of the target thickness on the π^- yields was investigated for the case of carbon targets. For that in the space of the chamber, two effective volumes were chosen and used both as a target and detector. For each volume one could estimate the resulting contribution of the both secondary processes — production of π^- mesons and their absorption. The results of the secondary interactions analysis in propane are summarized in table 1 for deuteron beam at 1 $GeV/nucleon$.

Table 1

Target size (C_3H_8)	$37 \times 18 \times 40 cm^3$	$62 \times 18 \times 40 cm^3$
Nb. of primary interactions	3508	2290
Nb. of π^- produced (N_{π^-})	415	290
Secondary interactions of π^- mesons :		
Stopping inside the eff. volume	35	35
Charge-exchange or absorption in flight	5	5
% of N_{π^-}	-9.6 ± 1.5	-13.8 ± 2.2
Exit from the eff. volume	26	24
Additional production of π^- mesons :		
In charged particle interaction	9	9
In neutral stars	24	30
% of N_{π^-}	$+8.0 \pm 1.5$	$+13.4 \pm 2.8$
Total contribution of secondary processes [%]	1.6 ± 2.1	-0.4 ± 3.5

One can see in table 1 that the contributions of these processes are increasing with the target length being increased. The contribution to the yield of π^- absorption mechanisms increases from 9.6% (for the first volume) to 13.8% (for the second volume), while in the processes of additional pion generation, these values are increasing from 8% to 13.4% when the target length increases. However, both of the processes compensate each other: the total contributions of secondary processes to the average multiplicity of pions produced in primary interactions are $-(1.6 \pm 2.1)\%$ and $-(0.4 \pm 3.5)\%$, respectively. So, one may expect that the resulting contribution of secondary interactions inside the thick target of the used configuration is small.

One can conclude that the additional production of π^- mesons due to the secondary interactions is compensated by the absorption process of negative pions inside the thick target.

The results of the yield investigation of π^- mesons from the extended targets are presented in table 2 for the deuteron beam at 1 *GeV/nucleon*. The types and sizes of targets are shown in the first row. The slight increase of the π^- yield per one inelastic interaction of the deuteron (the second row of table 2) should be explained by the increase of the relative neutron contents in the target (propane, carbon and beryllium) and only a part of it — by secondary effects.

Table 2

Types and sizes [g/cm^2] of targets				
Propane 16	Propane 26.6	Carbon 51.9	Beryllium 51.7	Beryllium [23] 370
Yield of π^- mesons per one inelastic interaction				
0.116 ± 0.008	0.122 ± 0.008	0.174 ± 0.010	0.190 ± 0.018	
Yield of π^- mesons per one projectile deuteron				
0.042 ± 0.003	0.066 ± 0.005	0.121 ± 0.007	0.135 ± 0.012	0.33
Energy fraction for one π^- meson production [GeV]				
48 ± 3	30 ± 2	16.5 ± 1.1	14.8 ± 1.3	6.1

The significant increase of π^- yield per one primary deuteron (the third row in table 2) is provided by the neutron contamination of the target as well as by the increasing of the target longitudinal size.

In the last column of table 2, the results of the theoretical calculation of the π^- yields are presented for the beryllium target of 200 *cm* in long and 8 *cm* in diameter exposed to deuteron beams. It is possible to see that with the increase of the target longitudinal size by seven times, one could expect the $\pi-$ yield to be 2.5 times greater and, correspondingly, the decrease of the primary energy quantity for the production of one π^- meson from 14.8 *GeV* to 6.1 *GeV* (the last row of the table 2) could be expected.

In our case to use the target with longitudinal size greater than 30 *cm*, was impossible as it should have been placed in a sensitive volume with magnetic field of 1.5 *Tesla* used to measure the momentum of the particles and their charges.

There was an intention to expose the propane chamber with two beryllium targets inside it to nuclei beams to make sure of the dependence of the π^- meson energy cost on the target longitudinal size. But these runs did not take place.

The π^- meson energy cost was investigated as a function of the beam energy. The energy beam 1.0, 2.0 and 3.3 *GeV/nucleon* was used. The results of this experiments are presented in table 3 [27].

Table 3

Reaction	$T_{beam}[GeV/A]$	$< N^{ev}_{\pi^-} >$	$< N^{o}_{\pi^-} >$	$\sigma_{in}[mb]$	$E/1\pi^-[GeV]$
dC (graphite)	1.0	0.17 ± 0.01	0.12 ± 0.01	459 ± 19[26]	17.0 ± 1.0
dC (propane)	1.0	0.16 ± 0.01	0.08 ± 0.01	425 ± 21[28 – 31]	24.0 ± 1.7
dBe	1.0	0.19 ± 0.02	0.14 ± 0.02	363 ± 13[26]	14.7 ± 1.6
dBe	2.0	0.50 ± 0.03	0.35 ± 0.02	340 ± 18[27]	11.6 ± 1.0
αBe	2.0	0.73 ± 0.05	0.52 ± 0.04	360 ± 30[27]	15.4 ± 1.1
dC (propane)	3.3	0.62 ± 0.03	0.32 ± 0.02	413 ± 20[28 – 31]	21.3 ± 1.2
αC (propane)	3.3	1.07 ± 0.05	0.57 ± 0.03	445 ± 22[28 – 31]	23.0 ± 1.3

Here $< N^{ev}_{\pi^-} >$ and $< N^{o}_{\pi^-} >$ are the pion multiplicities per one interaction and per one incident beam particle, correspondingly. The energy $E/1\pi^-$ needed to produce a negative pion is $AT_{beam}/ < N^{o}_{\pi^-} >$, where T_{beam} is the kinetic energy of the beam per nucleon and A is the number of nucleons of the beam nuclei.

It is seen from table 3 that the mean value of pion multiplicity increases while increasing of the beam energy and the A-number of the beam nuclei. But there is no significant gain in energy cost for the pion production in different reactions listed in table 3. It is seen that dBe interactions at 2.0 $GeV/nucleon$ are more preferable for pion generation and it seems not reasonable to increase further the beam energy. Still there is a problem of a more appropriate energy for the primary deuteron beam in the range of 1—2 $GeV/nucleon$.

There was also intention to expose the chamber to deuteron beam at 1.5 $GeV/nucleon$. But this experiment as that one with two beryllium targets inside the chamber, did not take place due to financial problems.

The presented data for different beam (deuteron, α -particles) and different targets (carbon, beryllium) have shown that the number of negative pions per interaction is increasing with A - number of projectile nuclei but still not enough for the energy gain in their production.

If to take into account that the heavier nuclei have a greater charge and the energy loss due to ionization in prolonged targets will be larger, then the deuteron beam is more preferable for pion production. Tritium is not desirable due to its radiation and worse ratio of charge to mass ($Z/M = 1/3$).

For practical application of μCF it is not enough to know the mean values of π^- mesons generated in nuclei collisions. It is important also to measure their momentum and angular distributions. The pions should be transported into convertor (vacuum space for pion decay) with minimal energy losses. After that the muons should enter the synthezator. It means that the target and decay volume should be inside the solenoid with a magnetic field focusing the negative particles. The solenoid sizes and the magnetic field should be optimal to the angular-momentum distributions of the pions and muons.

The detailed experimental momentum-angular correlations for dBe, dC, αBe interactions at 1 GeV and 2 GeV are presented in [27]. To illustrate the data, table 4 presents the average kinematic characteristics of π^- mesons for these reactions.

Table 4

Reaction $T_{beam}[GeV/A]$	dBe 1.0	dBe 2.0	αBe 2.0	dC(ext.) 1.0	dC(C_3H_8) 1.0
$< P_{\pi^-} > [GeV/c]$	$.274 \pm .002$	$.379 \pm .003$	$.363 \pm .006$	$.270 \pm .004$	$.314 \pm .005$
$< \theta_{\pi^-} > [deg.]$	$54. \pm 0.5$	$49. \pm 0.3$	$47. \pm 0.7$	$54. \pm 0.1$	$51. \pm 0.1$
$< P_t^2 > [(GeV/c)^2]$	$.033 \pm .001$	$.053 \pm .001$	$.048 \pm .001$	$.038 \pm .001$	$.043 \pm .001$
$< T_k > [GeV]$	$.175 \pm .002$	$.268 \pm .002$	$.250 \pm .005$	$.172 \pm .004$	$.209 \pm .004$
Nb. of events	4800	9800	2100	1200	1000

The comparison of the data has shown the following main features:

- the corresponding spectra have the same shape for different targets and primary energies;
- the momentum distributions for dC extended target are lower than those for dC interactions in propane;
- no significant effect of the thick target is seen in the angular distributions;
- the π^- transverse momentum squared distribution could not be fitted analytically by one exponential.

Unfortunately, the planned program was not fulfilled completely. The runs with dBe data-taking at 1.5 $GeV/nucleon$ and the length of beryllium target by two times greater, did not take place. Nevertheless, the existing experimental data may be useful further to calculate and optimize technical projects. It seems reasonable to solve the problem of decreasing the energy expenditure for pion production at the stage when all the parameters of the technical project for the whole complex are optimized.

4 Some remarks on the material of the target

There are some arguments to use a beryllium target instead of the lithium one. Beryllium-9 has the melting point 1315 C, density 1.848 g/cm^3 and it is successfully used for reactor constructing. Lithium-7 has the melting point 179 C, density 0.508 g/cm^3 and it is used as a liquid heating transfer. To produce the pions an accelerator with large electric current should be used. Then the target would be exposed to high temperature. It means that lithium should be isolated by a metallic vessel connected with a refrigerator. The presence of a metallic vessel will increase the low pion absorption and make difficult to place the target inside the solenoid. The density difference of these materials has shown that the beryllium target is more preferable.

5 Conclusion

The muon catalysis of nuclear fusion in hydrogen has attracted scientists from many countries. There are many interesting results in this field. In our short review we did not try to give a complete analysis of μCF. We believed it would be useful to emphasize some reasonable points in chronological order and present the problem in its dynamics and development. Many important works have not been touched here. We hope the authors of these articles would kindly apologize us for this.

The perfect answer for the question what muons can do, is still unclear. The new scientific results show the new possibilities. The problem has, undoubtedly, intellectual and practical interests. That is why the task of the lowest energy cost muon production is still important.

At present the new data have been taken by means of the 2-meter propane bubble chamber with an extended cylinder target inside exposed to beams of light relativistic nuclei from the Dubna synchrophasotron.

The cross sections of inelastic interactions of projectile deuterons and α-particles with different targets (Be, C - extended, propane), the multiplicity of π^- mesons and their kinematic correlations have been measured at beam energies of 1.0, 2.0 and 3.3 GeV/c.

The production energy expenditure of one negative pion in different reactions has been measured for the first time. The process of the π^- mesons production close to the lowest energy expenditure has been found. The dBe reaction at 2 $GeV/nucleon$ is the most preferable one among all the considered reactions. At least these data make possible to estimate the appropriate length of a target with A-number close to Be or C and indicate that the beam particle should be deuteron with energy approximately 1–2 $GeV/nucleon$.

The secondary processes inside the thick target have been investigated in detail. The investigation has shown that both types of secondary processes– production of π^- mesons and their absorption, compensate each other and their resulting contribution into the π^- yield from the extended target is an insignificant value.

The momentum-angular correlations of the π^- mesons emitted from the extended targets have been also measured. The comparison of the data for different targets has shown insignificant influence of the longitudinal size of the target on the angular distributions, and the momentum spectra are shifted to smaller values with increasing of the target thickness.

Thus, the new experimental data are important to define the optimal conditions of the negative muon beam production available for the muon catalysis of nuclear fusion.

At present the experimental investigations with the 2-m propane bubble chamber have been stopped, and the chamber, the device which allows to register all the charge particles in 4π - geometry, has been dismounted. A part of the experimental program was not fulfilled. Nevertheless, some problems were solved. Important experimental data have been taken and they may be used either for theoretical calculations or to improve and develop new experiments.

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Затраты энергии на рождение пионов (мюонов) для мюонного катализа слияния ядер

В работе изложены основные этапы накопления знаний по мюонному катализу синтеза ядер.

Затронута проблема использования мюонного катализа слияния ядер для практического получения энергии в гибридном реакторе. Обсуждаются вопросы получения $\pi^-(\mu^-)$-мезонов с наименьшими затратами энергии.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1995

Fadeev N.G., Soloviev M.I. E1-95-29

The Pion (Muon) Energy Production Cost in Muon Catalyzed Fusion

The article presents the main steps in the history of the study on the muon catalysis of nuclear fusion.

The practical application of the muon catalysis phenomenon to obtain the energy gain is briefly discussed.

The details of the problem to produce pion (muon) yield with minimal energy expenses have been considered in the paper.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1995