MEETINGS AND CONFERENCES

Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (31 October 1985)

Usp. Fiz. Nauk **148**, 719–725 (April 1986)

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences was held on 31 October 1985at the S. I. Vavilov Institute of Physics Problems of the USSR Academy of Sciences. The following reports were presented:

April 25

1. *A. A. Vorob'ev.* Muon catalysis of nuclear fusion reactions.
2. *M. V. Stabnikov.* New developments in holographic tracking detectors.
3. *V. S. Panasyuk.* New types of synchrotrons as dedicated generators of synchrotron and x-ray radiation.

Summaries of two reports are published below.

A. A. Vorob'ev. *Muon catalysis of nuclear fusion reactions.* In order to achieve fusion, for instance of tritium and deuterium nuclei, it is necessary for the nuclei to penetrate the Coulomb barrier. One possible method of solving this problem is to heat the medium to tens of millions of degrees, as is done in various types of thermonuclear devices. Another method, which is promoting much discussion lately, involves nuclear fusion near room temperatures with negatively charged muons acting as catalysts ("cold fusion"). For this method, the following simplified sequence of processes takes place:

$$d\mu + t \xrightarrow{\lambda_{dt}} t\mu + d \xrightarrow{\lambda_{dt\mu}} (dt\mu)^+ \begin{cases} \longrightarrow {}^4He + n + \mu^-, \\ \xrightarrow{w_{dt}} {}^4He\mu + n. \end{cases}$$

A negatively charged muon stops in the deuterium-tritium mixture and is captured into an orbit around a deuterium or a tritium nucleus, forming respectively a $t\mu$-atom or a $d\mu$-atom. In subsequent collisions of the $d\mu$-atom the muon is transferred from the deuterium to the tritium nucleus. This reaction rate is denoted by λ_{dt}. Then a mesomolecule $(dt\mu)^+$ forms with rate $\lambda_{dt\mu}$. This mesomolecule is an analog of the H_2^+ ions, but is smaller by a factor of 200. Consequently the deutrium and tritium nuclei are "confined" to a volume of radius $\sim 5\cdot 10^{-11}$ cm, which permits them to penetrate the potential barrier in less than 10^{-9} s. Immediately after fusion the compound-nucleus disintegrates, liberating an energy $Q = 17.6$ MeV. As a rule the muon is released by this process and may catalyze fusion reactions again and again. This will continue until the muon either disintegrates (muon lifetime $\tau_\mu = 2.2\cdot 10^{-6}$ s) or is captured by a ^{4}He nucleus (w_{dt} is the "sticking" probability of the muon to ^{4}He).

How many dt-fusion cycles must a single muon catalyze for μ-catalysis to become a source of energy? This question was recently investigated by Yu. V. Petrov[1] at the Leningrad Institute of Nuclear Physics (LINP) of the USSR Academy of Sciences. The result was that currently μ-catalysis may be practical only using a uranium blanket and only if a single muon catalyzes a number of dt-fusion cycles $X_c \geqslant 100$. At $X_c = 100$ the potential of μ-catalysis is comparable to that of electronuclear breeding—in addition, these methods could be combined in a single device.

But then, how many fusion cycles can a single muon really catalyze? Is there an absolute upper limit on this number valid in all circumstances? It appeared that there existed a definite answer to the latter question. Already in 1957 J. Jackson and Ya. B. Zel'dovich[2] calculated the muon sticking coefficient: $w_{dt} \approx 0.01$. It followed that $X_c \leqslant 100$. Later these calculations were repeated[3] taking into account that as the $(^4He\mu)^+$ ion decelerates the muon may be "shaken off." The limit $X_c \leqslant 110$ was obtained. Recently, however, the validity of this limit has been questioned. A method of measuring the muon sticking coefficient in the d–μ–d fusion reaction was developed at LINP of the USSR Academy of Sciences:

$$d\mu + d \xrightarrow{\lambda_{dd\mu}} (dd\mu)^+ \begin{cases} \longrightarrow {}^3He + n + \mu^-, \\ \longrightarrow {}^3H + p + \mu^-, \\ \xrightarrow{w_{dd}} {}^3He\mu + n. \end{cases}$$

Measurements[4] yielded the following result: $w_{dd|exp} = 0.122 \pm 0.003$. This experimental result was somewhat lower than the theoretical value $w_{dd|theor} = 0.147$. This discrepancy prompted theorists to reexamine the muon sticking problem. The L. I. Ponomarev group performed new calculations (see[5,6]) using the recently obtained exact wavefunctions of $dd\mu$- and $dt\mu$-molecules. The result was $w_{dd|theor} = 0.122$, in exact agreement with experiment. The same calculations yielded $w_{dt|theor} = 0.58\cdot 10^{-2}$, which corresponds to the upper limit on fusion cycles $X_{c|max} = 172$. Unfortunately no direct measurements of the quantity w_{dt} have been carried out: this remains one of the most important problems in μ-catalysis.

Clearly, it is possible to reach the limiting value $X_{c|max}$

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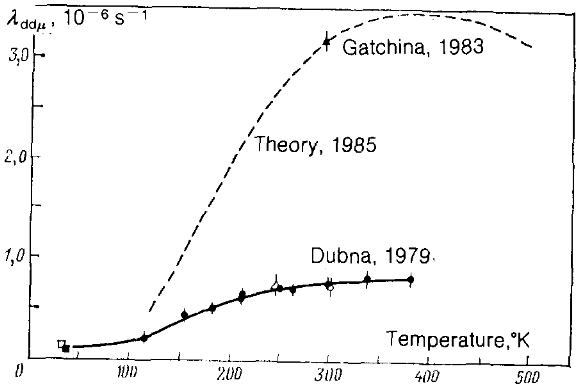

FIG. 1. The temperature dependence of the formation rate of $dd\mu$-molecules.

only if a single fusion cycle is completed on a time scale hundreds of times shorter than the muon lifetime. No so long ago this possibility appeared absolutely unrealistic. This was because the first μ-catalysis reaction discovered by L. Alavarez[7] in 1957 was the $d\mu + p \rightarrow (dp\mu)^+ \rightarrow {}^3He + \mu$ reaction. The reaction rate for this process was slow: $\lambda_{dp\mu} < 10^7\ s^{-1}$.[1)] An even slower reaction rate was found for the d–μ–d-fusion reaction at liquid hydrogen temperatures: $\lambda_{dd\mu} \simeq 10^5\ s^{-1}$. Such reaction rates made practical utilization of μ-catalysis utterly impossible. Hence interest in μ-catalysis waned.

The situation changed with the discovery at Dubna[9] that the quantity $\lambda_{dd\mu}$ is strongly dependent on temperature (Fig. 1). An analysis of this dependence led the Dubna theoreticians to the conclusion that there existed a resonant mechanism for $dd\mu$-molecule formation.[10] The determining factor for the reaction rate in this mechanism was the most weakly bound level of the mesomolecule. Having developed methods of percision analysis of the three-body Coulomb problem, the L. I. Ponomarev group proved the existence of such levels both in the $dd\mu$-molecule and the $dt\mu$-molecule. These calculations predicted a high reaction rate for the formation of the $dt\mu$-molecule.[11] And indeed, the very first experiment investigating the d–μ–t-fusion reaction (Dubna, 1981) verified the prediction $\lambda_{dt\mu|exp} > 10^8\ s^{-1}$. The Isotope exchange rate also proved to be high: $\lambda_{dt} = 2.9 \cdot 10^8\ s^{-1}$.

The Dubna results did much to stimulate further research in μ-catalysis. Several approaches to the problem were pursued. The experimental method developed at LINP proved very effective for the study of d–μ–d-fusion. This last reaction is not promising as a source of energy, but it is very similar to the d–μ–t-fusion reaction. At the same time, d–μ–d-fusion is much simpler to investigate experimentally, and the data is easier to interpret because the main reaction is not obscured by accompanying processes. Consequently, d–μ–d-fusion is a good proving ground for the μ-catalysis theory. In the LINP experiments all major parameters of d–μ–d-fusion were obtained to high precision. In particular, the formation rate of the $dd\mu$-molecule was determined (see Fig. 1, Gatchina, 1983). The result aroused much discussion because it exceeded the Dubna value of $\lambda_{dd\mu}$ by a factor of four. The LINP group repeated the experiment under various experimental conditions to demonstrate successfully the validity of their result.[4] Recently the LINP result was corroborated by an experiment performed at the Los Alamos meson facility (USA).

Concurrently, the L. I. Ponomarev group worked hard on improving the theory of μ-catalysis. An important step in their progress was the computation with unprecedented accuracy of the weakly bound levels in $dd\mu$- and $dt\mu$-molecules (-1.946 ± 0.001 eV and -0.634 ± 0.001 eV).[13] As noted above, these levels play a determining role in the μ-catalysis rate. The next problem was to compute the $\lambda_{dd\mu}$ rate in resonance formation of the $dd\mu$- molecule. Meticulous calculations accounting for all details of the reaction mechansisn finally yielded the result shown in Fig. 1 by a dashed line. The excellent agreement between theory and experiment illustrates the current high degree of understanding of the μ-catalyzed dd-fusion process.

Evidently these successes laid a solid foundation for the completion of a quantitative analysis of μ-catalyzed dt-fusion and work on this problem is currently in progress. However, in this process there are difficulties which did not arise in d–μ–d-fusion: the details of the muon transfer; the role of three-body collisions in $dt\mu$-molecule formation; the thermalization of $t\mu$-atoms. For this reason most of the data on d–μ–t-catalysis are at present being obtained by experiment. Experimental research is carried out in laboratories at LAMPF (USA), TRIUMF (Canada), SIN (Switzerland), and the Leningrad Institute of Nuclear Physics at the USSR Academy of Sciences.

The S. Jones group, working at the LAMPF meson facility, have recently reported impressive results.[14] This group investigated the neutron yield from a muon-irradiated deuterium-tritium mixture at 700 atm pressure and temperatures of up to 800 °K. It turned out that the d–μ–t-fusion rate increases with pressure and temperature (Fig. 2), reaching $\lambda_s = 1.6 \cdot 10^8\ s^{-1}$. Extrapolating this value to the limit of realistically achievable temperatures and pressures (the Jones group is planning to reach 2000 atm and 1000 °K in their next experiment), $\lambda_s \geqslant 2 \cdot 10^8\ s^{-1}$ may be expected. This implies that, if the "sticking" of the muon to the ${}^4He$ nucleus did not occur, a single muon could catalyze over 400 dt-fusion events over its lifetime!

This being the case a direct measurement of the sticking

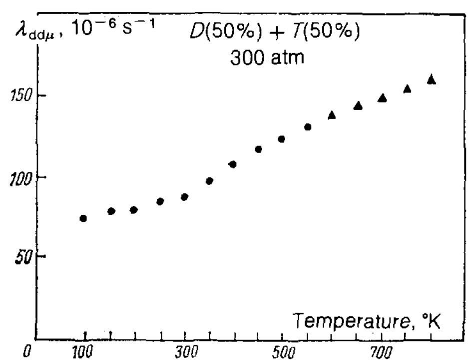

FIG. 2. The temperature dependence of the d–μ–t-fusion rate.

coefficient w_{dt} acquires great importance. Experiments are in preparation at LINP and Los Alamos. Currently, indirect estimates from experimental data of the Jones group indicate that $w_{dt} \approx 0.003$, a factor of two lower than the theoretical lower bound. Should this result be verified it will be possible to obtain $X_c \approx 200$ fusion cycles. Finally, a recent communciation from the Jones group reported 160 ± 10 fusion events catalyzed by a single muon in a deuterium-tritium mixture at liquid hydrogen temperatures.

In conclusion, research of the last several years has significantly changed our understanding of the muon catalysis of nuclear fusion reactions. The main breakthrough was the discovery of a resonance mechanism for the formation of ddμ- and dtμ-molecules that is responsible for a high rate of catalysis, especially in d–μ–t-fusion. The upper bound on the number of dt-fusion events catalyzed by a single muon has not yet been firmly established, but apparently it may be asserted that it is greater than 150. This implies that muon catalysis can be seriously discussed as a potential source of energy.

An expanded version of this report is published in "Proceedings of the XX winter school at LINP" (Leningrad, 1985).

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