Cold Nuclear Fusion

The electronlike particles called muons can catalyze nuclear fusion reactions, eliminating the need for powerful lasers or high-temperature plasmas. The process may one day become a commercial energy source

by Johann Rafelski and Steven E. Jones

Ordinarily the mention of nuclear fusion calls forth images of enormous magnets, powerful lasers and plasmas hotter than the center of the sun. These create the extreme conditions in which pairs of hydrogen atoms fuse, or join, creating helium and giving off energy that could be used to produce electric power. A less familiar but perhaps more promising kind of fusion, known as muon-catalyzed fusion, has a very different aspect: it circumvents the need for high temperatures entirely.

Muon-catalyzed fusion, which is also called cold fusion, can take place rapidly at room temperature in a simple chamber containing certain kinds of hydrogen known as deuterium and tritium. Particles known as negative muons are introduced into the chamber, and they form unusually tight bonds between the nuclei of some of the hydrogen atoms. The muon-bonded hydrogen nuclei then fuse, ejecting the muons, which can go on to catalyze other fusion reactions. The other atoms in the gas are essentially unaffected, except that each fusion increases the temperature of the gas as a whole. The heat from muon-catalyzed reactions might someday drive turbines for generating electricity.

Muon-catalyzed fusion is not limited to room temperature. The process has been made to work in liquid and solid forms of hydrogen at temperatures as low as 13 degrees Kelvin (degrees Celsius above absolute zero) and in gases at temperatures as high as 530 degrees C. Recent research suggests the reactions involved should be most efficient at about 900 degrees C.

The entities at the heart of the process, muons, are short-lived elementary particles. They are found in nature in secondary cosmic rays, which are produced when primary cosmic rays collide with the upper atmosphere. Muons can be made artificially by causing a fast-moving beam of ions (electrically charged atoms) from a particle accelerator to collide with a sample of ordinary matter such as carbon. The collisions produce particles called pions, which quickly decay to make muons in a process much like the one that takes place when primary cosmic rays strike the atmosphere.

Muons can carry positive or negative electric charge. A negative muon has properties quite similar to those of the electron but is about 207 times more massive. As we shall discuss, it is the muon's large mass that enables it to catalyze fusion reactions.

It is not yet possible to build a cold-fusion reactor that produces more energy than is required to operate it. A major stumbling block results from the short lifetime of muons, which decay, on the average, in about two microseconds (millionths of a second) after they are created. In that short time each muon must catalyze enough reactions so that the reactor as a whole can power the accelerator that generates muons. Until recently that goal seemed remote. In the past few years, however, theoretical and experimental advances have shown that under the proper conditions a muon may catalyze hundreds of times more reactions before it decays than had seemed possible. It is now conceivable that cold fusion may become an economically viable method of generating energy.

The possibility that negative muons could catalyze nuclear fusion was suggested on theoretical grounds by F. C. Frank and Andrei D. Sakharov in the late 1940's. The first experimental observation of muon-catalyzed fusion came by chance a decade later. Luis W. Alvarez and his colleagues from the University of California at Berkeley, analyzing the results of an unrelated experiment, noticed certain unusual patterns on films that recorded the tracks of particles through a bubble chamber. The Berkeley workers had not heard of the earlier suggestions by Frank and Sakharov, but, assisted by Edward Teller, they deduced that the patterns recorded the products of muon-catalyzed fusion reactions.

The discovery caused great excitement at first. As Alvarez remarked in his Nobel-prize acceptance speech in 1968, "We had a short but exhilarating experience when we thought we had solved all of the fuel problems of mankind for the rest of time." Unfortunately later calculations showed the reactions he had observed were too slow to generate useful energy: the average muon had time to catalyze at most only a single fusion before it decayed, producing too little energy to supply muons for later reactions. Most investigators went on pursuing other methods of stimulating fusion.

Nevertheless, some workers continued to study muon-catalyzed fusion. Investigators found that muons can catalyze fusion through several processes other than those first observed. The Alvarez group had seen reactions involving only deuterium and ordinary hydrogen, but it became clear that muons could catalyze reactions involving deuterium and tritium much more quickly. V. P. Dzelepov and his colleagues at the Joint Institute for Nuclear Research in Dubna found experimentally that the rate of one such process depended strongly on temperature, yielding more fusions per muon at higher temperatures.

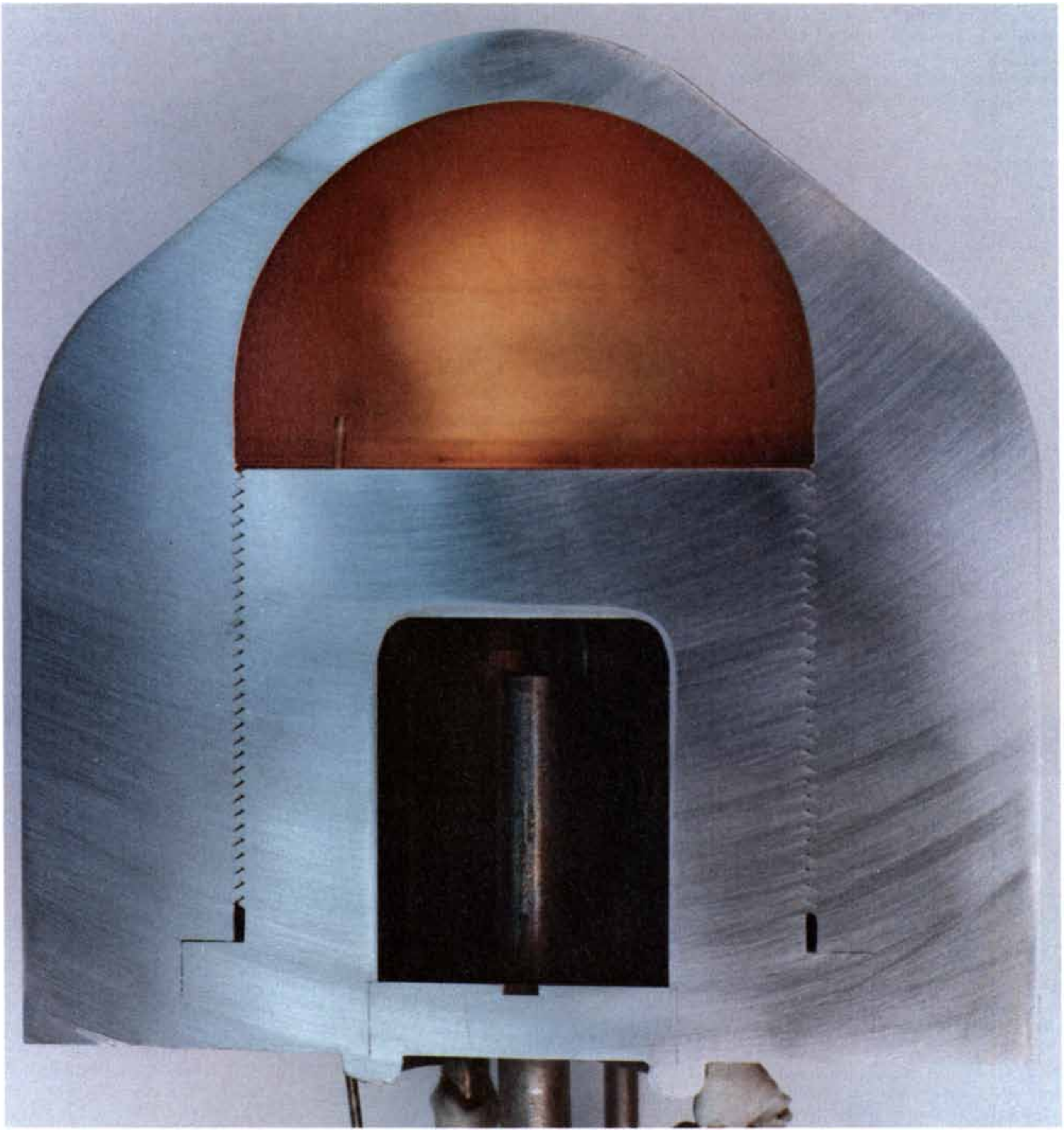
A model that explained the results was developed by E. A. Vesman of the Estonian Academy of Sciences in 1967. In 1977 S. S. Gershtein, L. I. Ponomarev and their co-workers in Dubna built on Vesman's model to predict that at certain temperatures, and in certain high-density mixtures of deuterium and tritium, muon-catalyzed fusion could occur much more rapidly—perhaps thousands of times more rapidly—than the processes first seen. The prediction led one of us

(Jones) and his colleagues to do experimental studies of muon-catalyzed fusion in deuterium and tritium.

What happens when a beam of negative muons enters a vessel of deuterium and tritium? To understand what ensues, it is first necessary to understand how deuterium and tritium differ from ordinary hydrogen.

An ordinary hydrogen nucleus is a proton: a massive, positively charged particle. In deuterium the nucleus is a proton bound to a neutron, which is slightly more massive than the proton and has no electric charge. In tritium the nucleus is a proton and two neutrons. In each kind of hydrogen atom the nucleus is orbited by an electron (which is negatively charged).

Like ordinary hydrogen atoms, deu-



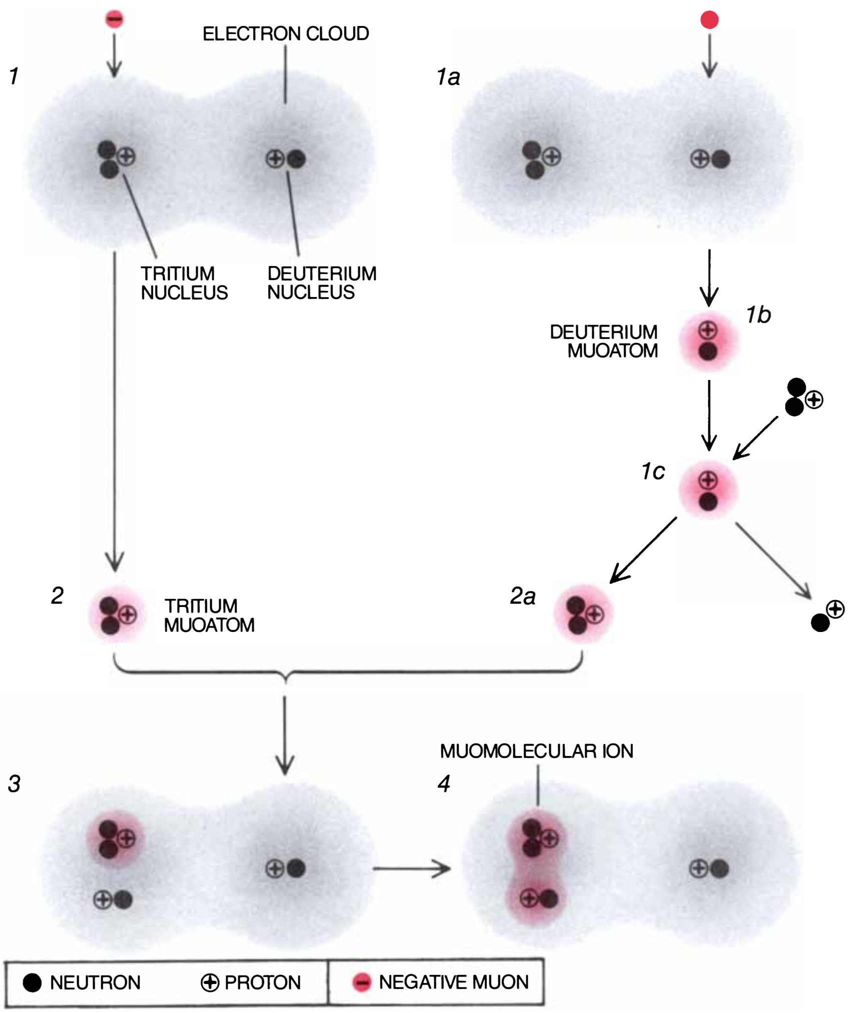
EXPERIMENTAL REACTION VESSEL in which cold nuclear fusion reactions take place is shown in cross section. The reactions occur in a gold-lined hemisphere (*top*) measuring two inches in diameter. A thin pipe fills the vessel with deuterium and tritium (forms of hydrogen). A beam of negatively charged muons is aimed from above at the vessel's cone-shaped top; it enters the reaction chamber by passing through the vessel's stainless-steel casing. The muons act as a catalyst, causing deuterium and tritium atoms to fuse, releasing energy and producing helium and neutrons. Liquefied gases are fed through a thick pipe into the hollow component screwed into the base of the reaction chamber (*bottom*). They cool the vessel for studies of how the rate of muon-catalyzed fusion reactions varies with temperature. Similar reaction vessels, built on a larger scale, could someday produce energy in a muon-catalyzed-fusion power plant. The vessel shown here was developed by Augustine J. Caffrey and Kenneth D. Watts of the Idaho National Engineering Laboratory, with help from Michael A. Paciotti and H. Richard Maltrud of the Los Alamos National Laboratory.

terium and tritium atoms combine in pairs to form molecules. In each molecule two nuclei are bound together by electrons, which form a unifying "cloud" between and around the positively charged nuclei. In a mixture of deuterium and tritium some molecules consist of two deuterium atoms, some of two tritium atoms and some of a deuterium atom bound to a tritium atom. Nuclei bound together in a molecule are relatively far apart; the distance between them is about 30,000 times greater than the radius of the nucleus itself.

A negatively charged muon traveling at high speed through a mixture of deuterium and tritium is slowed by collisions with the electrons that bind the molecules. The collisions usually knock the electrons out of their molecular orbits. Soon the muon is moving slowly enough so that as it displaces an electron it is captured into an orbit similar to the electron's. Almost immediately, however, the muon tumbles into a very tight orbit around one of the nuclei in the molecule.

It is because of the muon's large mass that it can orbit the nucleus so closely. In general, negatively charged particles such as electrons and muons can follow only certain stable orbits around nuclei. According to the laws of atomic physics, the size of a particle's smallest stable orbit is roughly proportional to the inverse of its mass. Because the muon is about 200 times more massive than the electron, it can follow an orbit about 200 times smaller than the electron's.

When the muon enters the tight orbit, the molecule it has invaded breaks apart; the muon and the nucleus it orbits—a "muoatom"—emerge with a small velocity. The muoatom can include a nucleus of deuterium or tritium. Because a tritium nucleus is more massive, it can bind the muon more strongly than a deuterium nucleus can. For this reason muons that originally bind to deuterium nuclei usually transfer, during some later collision, to a tritium nucleus. The events leading to the formation of a tritium muoatom—the slowing of the muon, its binding to a nucleus and any transfer from a deuterium to a tritium nucleus—can be made to take place in less than a thousandth of the muon's lifetime.



INITIAL STEPS of muon-catalyzed fusion bring a deuterium nucleus and a tritium nucleus into unusually close proximity. First a muon invades a molecule consisting of two nuclei held together by an electron cloud. The muon may collide with a tritium nucleus (*1*). Then, as a quantum-mechanical consequence of the muon's high mass, the muon falls into a very tight orbit around the nucleus, forming what is called a tritium muoatom (*2*). Alternatively (*1a*), the muon may collide with a deuterium nucleus, forming a deuterium muoatom (*1b*). In a later collision (*1c*) the muon can be transferred to a tritium nucleus, forming a tritium muoatom (*2a*). The tritium muoatom then penetrates the electron cloud of another molecule and collides with a deuterium nucleus (*3*). The tritium nucleus, the deuterium nucleus and the muon then combine within the molecule to form a muomolecular ion, in which the muon holds the nuclei together much as an electron binds nuclei in an ordinary molecule (*4*). Because of the muon's high mass, the nuclei in a muomolecular ion are approximately 200 times closer together than the nuclei in an ordinary molecule.

The events that take place in this first part of the muon-catalyzed fusion process are governed by the laws of atomic physics. The next steps in the sequence are governed by the laws of molecular physics.

The tritium muoatom is a small, electrically neutral object that wanders freely through the gas, easily penetrating the electron clouds of gas molecules. When it comes close to a deuterium nucleus in an ordinary molecule, it can combine with the nucleus to form what is called a muomolecular ion. In a muomolecular ion the muon binds the two nuclei (in this case a tritium nucleus and a deuterium nucleus) much as electrons bind the nuclei of a normal molecule. The muon can pull the two nuclei much closer together, however, because it is so much more massive than the electron. The distance between the nuclei in a muomolecule is usually about 200 times less than the distance between the nuclei in an ordinary molecule.

The small muomolecular ion can nest within the electromolecule (that is, the ordinary molecule). Because the muomolecular ion has a net positive charge (two positively charged protons and only one negatively charged muon), it takes the place of one of the positively charged nuclei in the electromolecule. Then the muomolecular ion and the remaining deuterium or tritium nucleus are bound to each other by electrons, just as the two nuclei in the muomolecular ion are bound together by a muon.

The speed with which the muomolecular ion forms is one of the key determinants of how many reactions each muon can catalyze. The ordinary molecule that hosts the muomolecular ion is critically important for its rapid formation.

For many years it was thought that the formation of the muomolecular ion is an inherently slow process, for reasons that concern the muomolecular ion's binding energy: the amount of energy the pair of nuclei gives off when it forms a muomolecular ion (which is equivalent to the amount of energy that would have to be added to split the nuclei apart). The muomolecular ion cannot form unless there is some mechanism for carrying away the binding energy.

An electron could serve the purpose; that is, the binding energy might be absorbed by an electron belonging to the electromolecule in which the muomolecular ion forms. The electron would then be ejected from the molecule at high speed. Unfortunately this simple mechanism is also a slow one. According to quantum mechanics, the electron can absorb such a large amount of energy only under certain relatively rare conditions.

There is a much faster mechanism, however: the one, in fact, that was suggested by Vesman in 1967. The mechanism depends on a resonance effect. The molecule hosting the muomolecular ion can vibrate in space. The molecule's vibrational states are quantized: only certain amounts of vibrational energy are allowed. In a sense the molecule is like a xylophone that has only a fixed set of tones. In Vesman's mechanism the energy given off by the formation of the muomolecular ion "rings" one of the vibrational states of the molecule—the molecule as a whole absorbs the binding energy and vibrates as a result.

The binding energies of muomolecular ions are usually about 100 times larger than the energies of normal molecules. The muomolecular ion involved in muon-catalyzed fusion, however, could not form by resonance unless it had a much lower binding energy, in order to match a vibrational energy level of the larger molecule. The muomolecular ion that forms by resonance is therefore quite loosely bound: it has a very low binding energy in relation to typical muomolecular energies. It was Ponomarev's achievement to show, by a series of detailed calculations, that such an unusual, loosely bound state can exist.

The resonance mechanism calls for precise tuning: the energy absorbed by the molecule must be equal to the energy of its vibrational state. The binding energy of the loosely bound muomolecular ion turns out to be slightly less than the energy of a vibrational state in the larger molecule. The muoatom and the deuterium nucleus can supply the extra energy if they have the right amount of kinetic energy when they collide to form the muomolecular ion. The kinetic energy of the colliding particles can be tuned by adjusting the temperature of the gas.

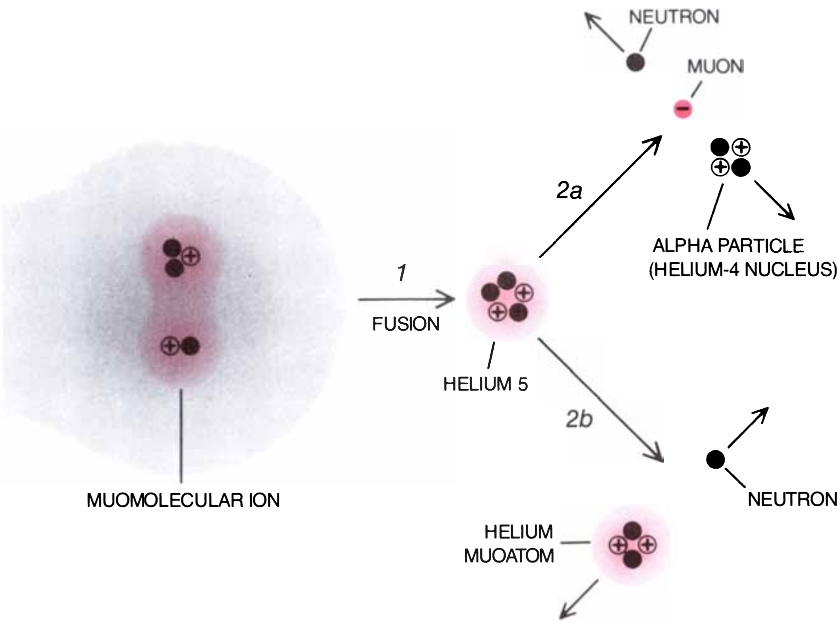
According to the resonance model, then, the temperature of the gas has a great effect on the rate at which muomolecular ions are formed. In 1982 one of us (Jones) and his fellow workers initiated a new experimental program in muon-catalyzed fusion at the Los Alamos Meson Physics Facility (LAMPF). Under the aegis of Ryszard Gajewski of the U.S. Department of Energy, we tested the predictions of the resonance model and found that the rate of muon-catalyzed fusion reactions does indeed vary with temperature in much the way that the theory predicts. To our surprise, we also found that the overall reaction rates were much more rapid than had been predicted; in one case the fast rates allowed about 150 fusions per muon, with the potential for still higher yields. These exciting discoveries helped to rekindle widespread interest in muon-catalyzed fusion.

After the muomolecular ion forms, it falls from its loosely bound state into a more strongly bound one, giving off energy that might be carried away by an electron. The nuclei in the strongly bound muomolecular ion are confined together in a very small volume. They repel each other because they both bear positive charges, but the muon repeatedly draws them together. Eventually the nuclei are united by a quantum-mechanical phenomenon known as tunneling: they pass through the "barrier" of their mutual repulsion until they are so close that the strong nuclear force (the force that binds protons and neutrons in nuclei) asserts itself. Now the laws of nuclear, rather than molecular, physics begin to govern events.

The nuclei fuse to form a single nucleus of helium 5, which has two protons and three neutrons. Soon afterward, this nucleus breaks up into an alpha particle, which is an ordinary helium nucleus (two protons and two neutrons), and a free neutron.

The reaction releases energy, which takes the form of kinetic energy: the alpha particle and the neutron move away from each other at high speed. The muon is usually left behind, and so it is free to repeat the cycle. It acts as a true catalyst for nuclear fusion.

Sometimes, however, the alpha particle created in the fusion reaction captures the negatively charged muon by virtue of its own positive charge, there-



FUSION occurs as a tritium nucleus and a deuterium nucleus in a muomolecular ion combine, forming a helium nucleus and a free neutron and releasing energy. Because the tritium and deuterium nuclei in the muomolecular ion are held close together by a muon, the strong nuclear force can cause them to fuse (*1*) into a helium-5 nucleus orbited by a muon. The helium-5 nucleus breaks up almost immediately. Usually (*2a*) it breaks into a neutron, an alpha particle, or helium-4 nucleus, and a muon. Sometimes, however (*2b*), the positively charged alpha particle captures the negatively charged muon, forming a helium muoatom and preventing the muon from catalyzing another reaction. In any case, the fusion releases kinetic energy: the neutron and the alpha particle move away at high speed.

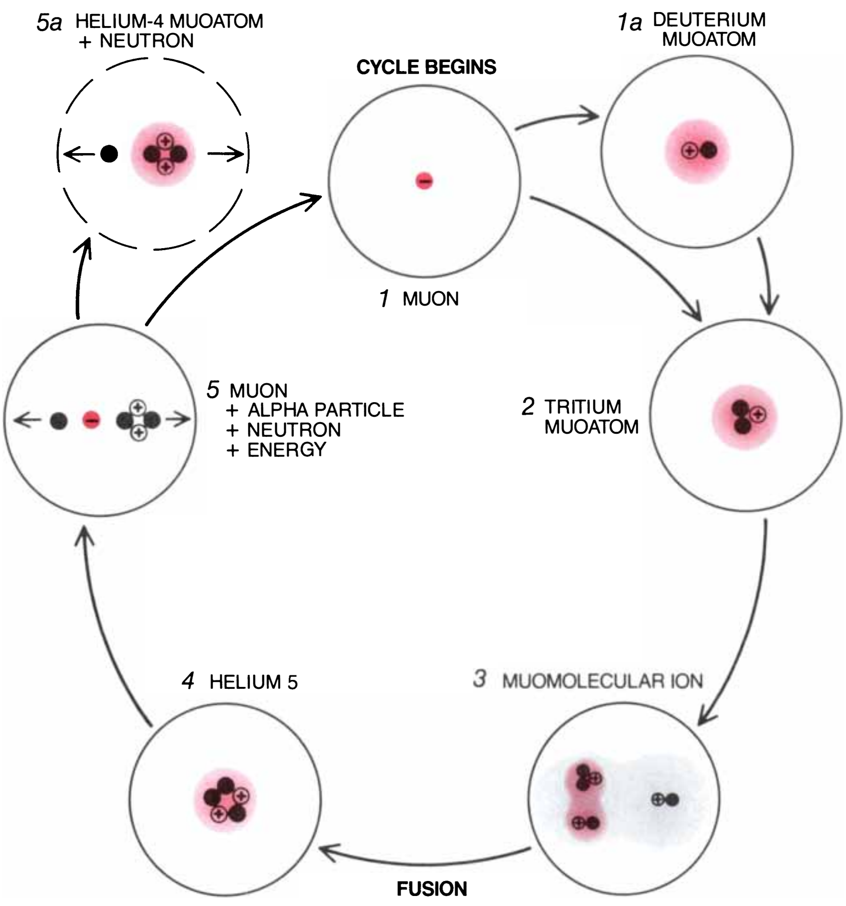
by preventing the muon from going on to catalyze another fusion reaction. Even if the muon is captured, there is still some probability that it will be stripped away by a collision, because the alpha particle is initially moving rapidly through the dense gas in the reaction vessel. In 1981 Gershtein and his collaborators and, independently, Giovanni Fiorentini and Luciano Bracci of the University of Pisa found that about 25 percent of the muons that stick to alpha particles are eventually stripped free. More recently James S. Cohen of the Los Alamos National Laboratory has suggested that perhaps as many as 40 percent are stripped free. There is still much room for further understanding of this process. If the muon sticks to the alpha particle until the pair comes to rest, it will remain bound until it decays.

The frequency with which a catalyzing muon sticks to an alpha particle, breaking a chain of fusion reactions, is the primary obstacle to muon-catalyzed fusion. Unfortunately it is difficult to calculate the sticking probability accurately because the multibody reactions involved are so complex. In 1957 J. David Jackson, then at Princeton University, first recognized that the catalyzing muon could be carried away by the alpha particle in about 1 percent of fusion reactions. He therefore postulated that no more than 100 fusion reactions per muon could ever be achieved.

The LAMPF experiments, which saw well over 100 fusions per muon, led to theoretical reconsideration of the sticking probability as well as to additional experiments. Data from the LAMPF experiments, as analyzed by Allen N. Anderson of Idaho Research, Inc., showed that the alpha-muon sticking probability is about .4 percent or less under certain conditions—less than half the long-standing theoretical value. These surprising results have since been confirmed by experiments at the Swiss Institute for Nuclear Research (SIN), led by Wolfgang H. Breunlich of the Austrian Academy of Sciences and Jean-Claude Petitjean of SIN, as well as by experiments at the Japanese high-energy physics laboratory under the direction of Kanetada Nagamine.

Theoretical readjustments, due in part to David M. Ceperley and Berni J. Alder of the Lawrence Livermore National Laboratory and to Michael Danos of the National Bureau of Standards, Berndt Müller of the University of Frankfurt and one of us (Rafelski), have removed much of the disagreement between the theory of muon-alpha sticking and the experimental results. Important questions are still open, however. In an effort to find answers a major international effort is beginning at the Rutherford Appleton Laboratory under the leadership of Jones and John P. Davies of the University of Birmingham. The investigators will measure the sticking probability directly by using conventional particle-physics techniques to record all the products of fusion reactions.

In parallel with the experimental effort, a major theoretical program has been launched under the leadership of Hendrik J. Monkhorst and Krzysztof Szalewicz of the University of Florida and Lawrence C. Biedenharn, Jr., of Duke University. The workers hope to gain further understanding of the intricate resonance phenomena.



REACTION CYCLE of a cold-fusion reaction starts and ends with a free muon (*1*). A tritium muoatom forms (*2*), sometimes by way of a deuterium muoatom (*1a*). The muoatom combines with a deuterium nucleus to form a muomolecular ion (*3*), which fuses to make a helium-5 nucleus (*4*). The helium 5 splits into an alpha particle and a neutron, releasing energy (*5*). If the muon sticks to the alpha particle (*5a*), the cycle is interrupted because the catalyst has been removed; sticking is a primary obstacle to the development of muon-catalyzed fusion. If the muon does not stick, it is free to begin another cycle (*1*).

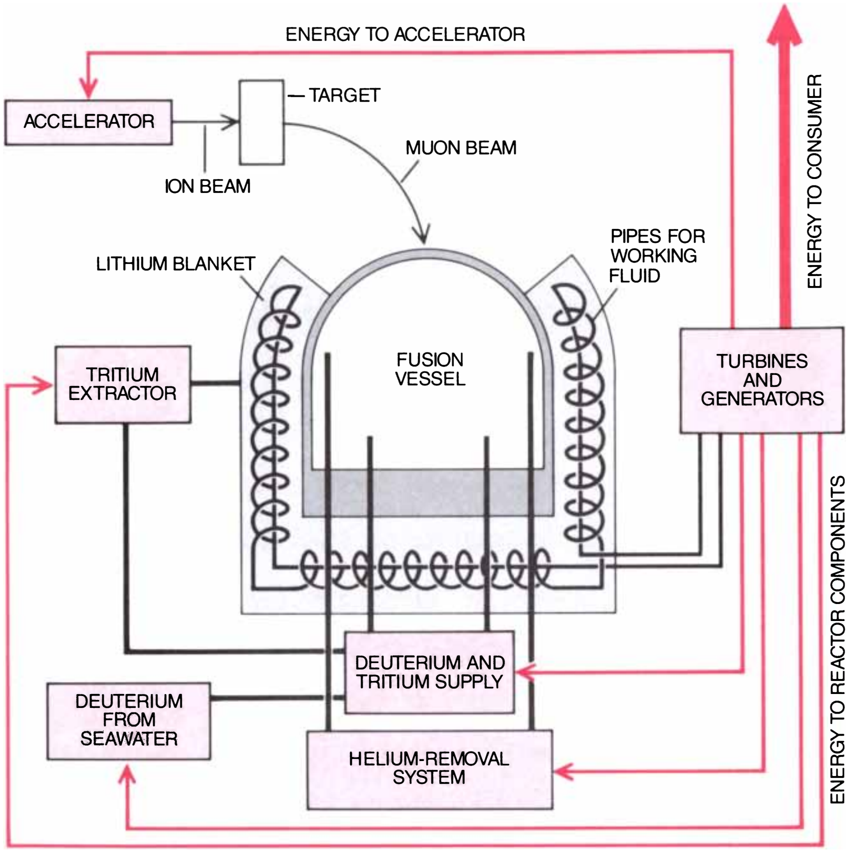
How might muon-catalyzed fusion serve as a practical source of energy? Although there has been little time to evaluate the implications of the recent discoveries, a number of possibilities have begun to emerge. In addition to the number of fusions per muon, the efficiency with which muons can be generated in the first place may determine which scheme can become viable. The energy equivalent of the muon's mass is roughly equal to the energy gained from six fusion reactions; in other words, an ideal, perfectly efficient muon-generating machine could create one muon for every six muon-catalyzed fusions taking place in the separate reaction vessel. Unfortunately the actual energy cost of creating a muon is at least 20 times greater. Advances in the technology of particle accelerators may well bring this cost down.

The cost of producing muons has been explored at CERN, the European laboratory for particle physics, by Magnus Jändel of the University of Uppsala and one of us (Rafelski). Our study shows that a single muon could be created by aiming an ion beam at a vessel of deuterium and tritium at an energy cost equivalent to between 100 and 500 fusion reactions. As the LAMPF experiments have shown, the muon thus produced could go on to catalyze well over 100 fusions.

One concept for generating energy by muon-catalyzed fusion was proposed in 1980 by Yu. V. Petrov of the Leningrad Institute of Nuclear Physics, and was based on the assumption that no more than 100 fusions per muon were possible. Petrov suggested a hybrid of muon-catalyzed fusion and nuclear fission. In addition to producing steam for driving turbines and dynamos directly, the fusion chamber would also serve as a source of neutrons for breeding nuclear fuel to be used in a fission-power plant.

A similar fusion-fission concept was proposed by Marshall N. Rosenbluth, Shalom Eliezer and Toshiki Tajima, then working at the University of Texas at Austin. In this scheme muons for the fusion process would be produced by aiming a high-energy beam of ions directly at the chamber of deuterium and tritium where the fusion reactions are to take place. The muons would then not need to be transported from a separate accelerator to the reaction vessel. As in Petrov's scheme, the muon-catalyzed fusion would provide neutrons for breeding fission fuel.

In addition to these concepts, a pure fusion reactor may also be possible. Such a reactor would have several advantages over fission reactors and fusion-fission hybrids. For one, the "ash" inevitably produced by the fusion process is helium, a harmless gas, rather than radioactive waste. For another, the materials required for fueling fusion reactions are abundantly available in seawater (which contains plentiful deuterium, as well as lithium that can be used to make tritium).



COMMERCIAL COLD-FUSION REACTOR could be built with existing technology. To make the required muons, a particle accelerator directs a beam of ions (charged atoms) at a target made of a substance such as deuterium or lithium. The resulting muon beam is guided into a reaction vessel supplied with deuterium (which can be collected from seawater) and tritium. There the muons catalyze fusion reactions. A purifier removes the helium produced by the reactions. Neutrons from the fusion reactions collide with a blanket of lithium, producing tritium and helium. The tritium is channeled into the fusion vessel and the helium is removed. Heat from the fusion reactions vaporizes a working fluid that is piped through the lithium blanket. The vapor spins a set of high-pressure turbines that run electric-power generators. Some of the electricity powers the particle accelerator, pumps and other components of the reactor. The rest is sold to consumers.

The zoo of elementary particles is a large one, and it is conceivable that some particle other than the muon might also be able to catalyze fusion. As George Zweig of the California Institute of Technology has suggested, free quarks (if they are ever found) could catalyze fusion reactions. Nevertheless, the muon suits the role remarkably well. Each muon can catalyze a long series of reactions, both because the resonance mechanism makes it possible for muomolecular ions to form quickly and because each muon has a good chance of being freed after a fusion event to catalyze another reaction. It also happens that the temperature at which the resonance mechanism should work best—about 900 degrees C., according to Melvin Leon of LAMPF—is also near the temperature at which many energy-generating systems, such as high-pressure steam turbines, are most efficient.

At much higher temperatures the resonance mechanism would ensure that fusion would proceed more slowly: the increased kinetic energy of the colliding muoatom and molecule, when it is added to the binding energy given up by the muomolecular ion, would be more energy than the larger molecule could readily absorb. This has two important implications. First, it means that a muon-catalyzed fusion reactor would not be susceptible to runaway reactions or meltdown. Second, it implies that muon-catalyzed fusion cannot be used as the basis for thermonuclear weapons.

Historically, pioneering research in physics tends to precede applications beneficial to society by one or two generations. The physics of exotic particles is now entering a stage at which applications are emerging; muon-catalyzed fusion is a prominent example.

In the case of muon-catalyzed fusion, the applications that are beneficial to society may themselves produce spin-offs that aid basic research. For instance, in the fusion reactor only negative muons would be needed, but a large number of positively charged muons would also be produced by the muon-generating mechanism and would therefore be available for the purposes of pure research. Ready availability of a large number of positive muons could open the door to fuller understanding of the enigmatic muon itself. Muon-catalyzed fusion thus could foster a close symbiosis of fundamental research and advanced technological applications.

Aside from its possible technological applications, research on muon-catalyzed fusion touches on many areas of modern physics. The processes involved depend on the laws of molecular, atomic, nuclear and particle physics. Research on muon-catalyzed fusion challenges our ability to combine concepts from these diverse fields and deepens our knowledge of each.