EXOTIC PARTICLE CATALYSIS†

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Catalysis is a familiar concept in chemistry. Some special material such as platinum in an automobile catalytic converter facilitates a chemical process but is not itself used up in the process. In a car the platinum remains and can be salvaged. There can be problems in chemical catalysis. For example, in a car the catalytic converter can become clogged or poisoned by lead-based products. In other catalysis reactions, the catalytic agent can be gradually exhausted.

Catalysis can also occur in certain nuclear reactions. In the famous solar carbon cycle that is the source of much of the solar power, carbon takes part in the nuclear reaction but is never used up. Instead, hydrogen is fused into helium with the release of energy.

An elementary particle, the muon, has been shown to have catalytic properties somewhat analogous to carbon in the solar nuclear cycle. There has also been wide speculation of the possible existence of two other types of elementary particles that could cause nuclear catalysis -- magnetic monopoles and fractionally charged particles sometimes called free quarks. While the catalytic properties of each of these particles is different, each has the possibility of catalyzing large amounts of energy, equivalent or substantially greater than the amount of energy available from hydrogen fusion. Two of these processes, muon and quark catalysis, represent substantial short cuts to the process of hydrogen fusion.

Hydrogen fusion is exactly the process mentioned earlier that gives rise to solar energy. Inside the sun hydrogen fusion proceeds rather easily, although fortunately, still quite slowly since we would be burnt to cinders otherwise. On the surface of the earth hydrogen fusion is hard to achieve. Basically, two deuterons must be forced close enough together so they form helium three and a neutron or tritium plus a proton. When this happens several MeV of energy is released as kinetic energy of the final products. The problem is that the two deuterons both have positive electric charges so that they repel each other up to about the point they start to touch. To overcome this repulsion it's necessary that the two deuterons collide at velocities corresponding to temperatures of millions of degrees.

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†This material was not presented at the Round Table. In part, it represents an abstract of some of the information on quark catalysis presented by George Zweig.

Two "conventional" approaches have been used for hydrogen fusion. One is to create a very hot plasma and confine it in a very large magnetic bottle. Figure 1 illustrates the size and complexity of such a device. The second is to take a pellet of heavy hydrogen a millimeter in diameter and compress it thousands of times using focused laser or particle beams. The laser energy and the resulting compression heats the pellet to the necessary temperature. Neither of these processes is easy. After investments of billions of dollars, neither approach is anywhere near break-even. This does not mean that these approaches won't work. It does imply that both are incredibly complicated and ultimately may require expenditures of tens of billions of dollars to realize their potential.

Muon catalysis short circuits these problems. In an earlier section Steve Jones has discussed this process in some detail. Only the bare bones of the process will be reviewed here. Negative muons, essentially heavy electrons, are produced from the radioactive decay of pi mesons. These muons live only several millionths of a second. In a typical

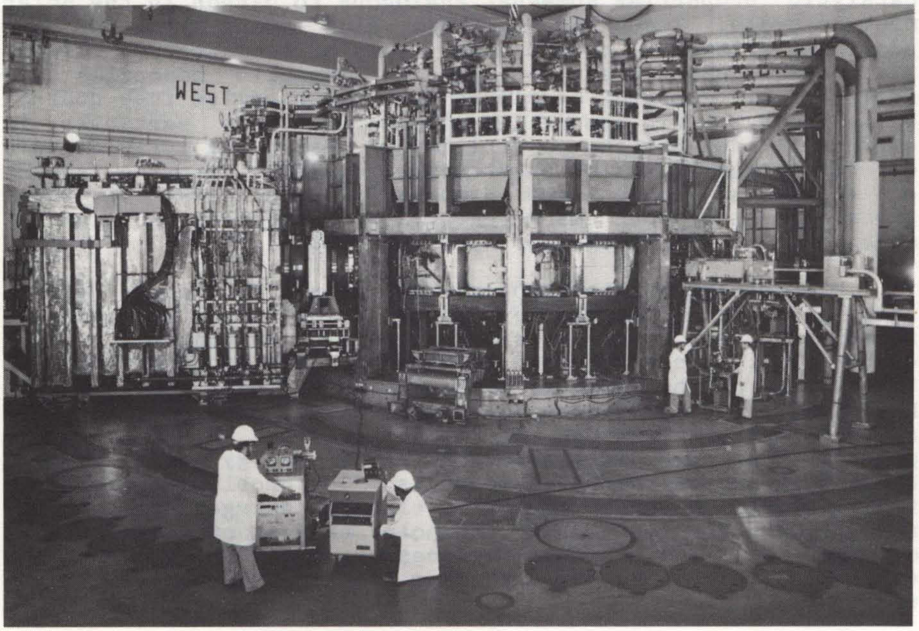

Fig. 1. Tokamat Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory. This illustrates the complex equipment needed to even study "conventional" hydrogen fusion.

collision of two protons at one billion volts several pions will be produced and they in turn will give rise to one or two muons. If a muon is put into a heavy-hydrogen mixture of deuterium and tritium it will form a very tightly bound muonic molecule about 1/200 the size of an ordinary molecule. Basically the muon mass, two hundred times the electron mass, sets the size of the molecule. As a result the deuteron and the tritium ion are pressed very close together. In a trillionth of a second they fuse together and the muon is freed to catalyze again.

Jones and his group working at Los Alamos have shown that a muon in a high pressure mixture of heavy hydrogen can produce hundreds of fusions before it expires. Further, they have found that there is little poisoning or blind alleys that the muon can enter where catalysis stops. These results have been unexpected; early calculations had suggested that each muon would catalyze only a few reactions. Indeed, the Jones results are quite near energy break-even. Each catalysis produces roughly 20 MeV of energy so that a single muon can yield 3 GeV during its lifetime. The energy investment to produce the muon is on the same order. Clearly, if the process could be further enchanced it would be possible to more than break even.

It is interesting to ask why the original estimates were low. A very important factor was the view that the lifetime of the muon was short -- only two millionths of a second. While this is true it is long compared to the time to catalyze a reaction. Early investigators also felt the muon catalysis rate would be low. The work of the Jones group has shown that a resonance interaction substantially enhances the rate. Finally Russian theoreticians had suggested that muons would often get stuck on Helium ions and be lost to the catalysis chain. Early experiments seemed to confirm these results so no one pursued the difficult but more promising possibility of using high concentrations of tritium.

The recent success of the Los Alamos investigations illustrates the need for experiments in exotic areas such as catalysis. It is hard for the theoretical physicist to cascade assumption upon assumption. The subtle effect of a resonance may escape notice or not be worth considering unless there is some experimental guidance. In muon catalysis the situation has turned out to be more favorable than originally anticipated. More often, additional problems are found and the original optimism fades. This is somewhat the problem for "conventional" hydrogen fusion. It could also be the case later for muon catalysis when, for example, the formidable problem of removing heat from a very high pressure vessel is faced.

Many different "elementary" particles like the muon have been identified. These particles range from neutrinos, massless particles with almost no interactions with matter, through electrons, one of the principal constituents of the atom, through protons and neutrons, the heavier heart of the atom, on up to the intermediate boson, a particle one hundred times as heavy as the proton. Some of the particles are more elementary than others. The proton, for example, is built up out of three fractionally-charged quarks.

Some of these particles are not directly observable. Quarks, as they are conventionally understood, are the best illustration. To all intents and purposes no free particle has ever been observed with an electric charge corresponding to a fraction of the charge on an electron. A set of observations at Stanford over a period of some years is open to grave questions since no one else has been able to repeat the experiment and it recently failed to pass a double blind trial. When the quark concept was first introduced the absence of free quarks was a serious stumbling block. Theory has now made a silk purse out of this sow's ear with the concept of color confinement. In essence, quarks carry a color charge in addition to their electric charge. Free color cannot appear so that quarks must always be paired off. Color confinement does much more than explain the absence of free quarks and has become the foundation of the modern theory of the nuclear strong interactions.

In addition to the known particles there is also a shopping list of particles that may very well appear on the scene in the near future. Characteristically these particles are heavier and decay quickly. Here a more powerful accelerator, such as the Tevatron or the Superconducting Super Collider (SSC) now under serious consideration, may be needed to unlock the undiscovered elementary particle. An illustration is the "top" quark, the expected twin to the third generation bottom quark discovered at Fermilab in 1977. Some would claim that evidence has already been found for the top quark at CERN in Europe. A set of fourth generation quarks and leptons may also appear. This would add to a chain that already includes the electron, the mysterious muon (its second generation partner), and a tau meson discovered at SLAC in California several years ago.

As noted earlier many of these particles are expected to be extremely unstable and decay almost immediately. This does not have to be! If some new property similar to color was found it might be very hard for the particle to decay. An illustration is a magnetic charge similar to the electric charge.

To complete the list of possibilities there is an enormous Chinese menu of proposed but undiscovered particles. Some of these proposals have large bands of followers, others only one or two. Given an experimental effect, right or wrong, a facile theorist can come up with at least one explanation. For example, a recent experimental artifact, the zeta, did not survive later experiments but generated between ten and one hundred sophisticated theoretical explanations. Some hypothetical particles have been discussed for fifty years, others for fifty days. Some may even turn out to exist.

Two particles of this class are particularly germane to catalysis -- the magnetic monopole and the free quark.

The first hypothetical particle that was discussed as a possible catalysis agent was the free quark. Recall that conventional quarks are confined and that there is no evidence for free quarks confirmed by independent experiments. On the other hand, maybe a new turn in the theoretical road could lead to free fractionally charged particles. Perhaps some quarks were freed in the very early moments of the universe and the experimental searches have been in the wrong place.

There is an interesting anecdote in this regard. George Zweig, one of the fathers of the quark concept, recounted a story at this Round Table about Hertz (Gustav, the physicist, not the car rental agency) and the discovery of the electron. Hertz, an eminent physicist of his day and the discoverer of radio waves, looked for the free electron in the 1880s. In the process he built the first cathode ray or TV tube but he did not find any electrons. Partly because of the weight of his result it was almost 15 years before J.J. Thompson (the Avis of the electron discovery) actually found a free electron. All of modern electronics flowed directly out of Thompson's discovery of the free electron! One might almost argue that the weight of Hertz's negative result slowed the development of modern electronics by an equivalent fifteen years and thereby affected every aspect of the history of the twentieth century. By inference, Zweig implies that the weight of quark color confinement as a theory has discouraged people from searching hard enough for free quarks in the twentieth century.

Free quark catalysis proceeds much like muon catalysis. When a free quark with charge -4/3 (not a garden variety quark) stops in hydrogen, say a mixture of deuterium and tritium, it will be captured on a molecule and form a highly excited but tightly bound quark-molecule system. In the process of de-excitation the original molecule breaks and a quark-deuteron or quark-triton ion with a charge of -1/3 is formed. The size of the ion will be much smaller than a normal atom. That size will be determined by the lighter of the two particles in the quark atom, either the quark or the deuteron (or triton). The basic size of an atom is set by the so-called Bohr radius which is inversely proportional to the reduced mass of the system. If the quark mass is a thousand times larger than the electron mass the ion will be a thousand times smaller.

The exotic negative ion will attract another nucleus to form a quark molecule. This quark molecule is very tightly bound. For a quark that is much heavier than a deuteron the binding energy is on the order of 100 keV, giving rise to velocities between the nuclei corresponding to temperatures of a billion degrees. Eventually the two nuclei in that quark molecule will fuse. In most cases the quark will be freed and go on to catalyze again. Zweig estimates that the upper limit for quark-molecule formation time would be about a second. The actual fusion time would be about 10^{-16} seconds. As with muon fusion there will be a substantial energy release. Some of these channels are summarized in Table I. One mole of quarks,

Table I.

Reaction	Energy released (MeV)
$pQp \rightarrow d + e^+ + \nu + Q$	0.4
$pQd \rightarrow He^3 + Q$	5.5
$pQt \rightarrow He^4 + Q$	19.8
$dQd \rightarrow t + p + Q$	4.0
$\rightarrow He^3 + n + Q$	3.3
$\rightarrow He^4 + Q$	23.9
$dQt \rightarrow He^4 + n + Q$	17.6
$tQt \rightarrow He^4 + 2n + Q$	11.3
$\rightarrow He^6 + Q$	12.3
$He^3Qd \rightarrow He^4 + p + Q$	18.4
$He^3Qt \rightarrow Li^6 + Q$	15.8
$\rightarrow He^4 + d + Q$	14.3
$\rightarrow He^4 + p + n + Q$	12.1
$He^3QHe^3 \rightarrow He^4 + p + p + Q$	12.9
$He^3QHe^4 \rightarrow Be^7 + Q$	1.6

that is, one to ten grams of quark matter, would be able to catalyze 10^{16} BTUs per year or a good fraction of the annual U.S. energy needs. (Bear in mind that one gram of free quarks are a lot of non-existent particles -- roughly a trillion-trillion.) As with muon catalysis, there are blind alleys the quarks can fall into. Perhaps once in a hundred times the quark will be trapped on a helium three nucleus resulting in a very small positive ion. Because of the positive charge this ion will be repelled from other nuclei and no longer catalyze. However, there are ways the quark could be recovered. For example, the helium three could be separated and exposed to thermal neutrons. Helium three has a very large cross section for thermal neutrons and breaks apart when it is hit thus freeing the quark. Yet another possibility is to use laser heating to strip off the quarks.

Quark fusion is also possible with free quarks having a charge of -2/3. However, it is then necessary to have two quarks to bind the deuteron. It should also be possible to induce fission with heavy quarks.

As noted earlier, no free quarks have been found. One possibility is that no one has looked in the right place. George Zweig points out that the chemistry of fractionally charged particles is quite different from ordinary chemistry. In essence every atomic element is tripled when a free fractionally charged quark is attached to a nucleus. For example, if a quark with charge -2/3 is attached to a helium nucleus, there is a net positive charge of 4/3. It will tend to be electro-negative, attach electrons and form ionic bonds. Zweig estimates the radius would be around that of fluorine so it might substitute in minerals containing fluorine. This tripling of the periodic table produces a vast body of exotic chemistry. Part of the new periodic table associated with hypothetical free quarks is shown in Table II. It is small wonder that there remain parts of this chemistry that are still uncertain.

With this uncertainty one can imagine that no quarks have been found, not because of the physics, but because the searches were in the wrong place. Under those circumstances, knowledge of quark chemistry would be equivalent to owning a treasure map or a license to form the International Quark Mining Corporation. Indeed, George Zweig was unwilling to have his Round Table talk published because his lawyer had advised him against it.

The magnetic monopole is the granddaddy of hypothetical particles. (Magnetic monopoles were discussed in an earlier section by Robert Fleischer.) The system of a north or south pole of a very long bar magnet acting on one pole of a similar magnet behaves very much like two isolated electric charges. Ergo, why not an isolated magnetic charge? In point of fact all the magnetic effects that are observed are due to circulating electric currents. Fifty years ago Paul Dirac looked at the possibility of magnetic charges. An interesting and surprising result of his work was an explanation for why

PERIODIC TABLE $Z = N + 1/3$

Key (each element cell):

X	X′
ELT_N	
IP	EA

Cell entries below are given as: Element$_N$ — X, X′; IP, EA

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
H_1 — 1.44, .89; 2.33, .55																	He_2 — 1.90, 1.82; 3.72, .08
Li_3 — .56, .30; .86, .26	Be_4 — .69, .64; 1.33, .05											B_5 — .81, .51; 1.32, .30	C_6 — 1.04, .56; 1.60, .47	N_7 — 1.16, .83; 1.99, .32	O_8 — 1.25, .68; 1.92, .57	F_9 — 1.59, .77; 2.36, .83	Ne_{10} — 1.46, 1.37; 2.83, .10
Na_{11} — .53, .29; .81, .24	Mg_{12} — .54, .52; 1.06, .02											Al_{13} — .58, .33; .91, .25	Si_{14} — .75, .37; 1.12, .38	P_{15} — .86, .52; 1.39, .34	S_{16} — .95, .44; 1.39, .51	Cl_{17} — 1.19, .49; 1.69, .70	Ar_{18} — 1.04, .95; 1.99, .09
K_{19} — .44, .22; .66, .22	Ca_{20} — .46, .34; .80, .12	Sc_{21} — .54, .32; .86, .22	Ti_{22} — .56, .35; .91, .22	V_{23} — .59, .34; .93, .25	Cr_{24} — .60, .34; .94, .26	Mn_{25} — .63, .37; 1.00, .25	Fe_{26} — .66, .40; 1.05, .26	Co_{27} — .67, .42; 1.09, .24	Ni_{28} — .68, .39; 1.07, .28	Cu_{29} — .71, .36; 1.07, .35	Zn_{30} — .68, .57; 1.24, .10	Ga_{31} — .56, .31; .87, .24	Ge_{32} — .73, .37; 1.11, .36	As_{33} — .80, .47; 1.27, .33	Se_{34} — .89, .41; 1.29, .48	Br_{35} — 1.07, .43; 1.51, .64	Kr_{36} — .91, .83; 1.75, .08
Rb_{37} — .40, .20; .60, .20	Sr_{38} — .43, .33; .76, .11	Y_{39} — .54, .30; .83, .24	Zr_{40} — .57, .33; .90, .24	Nb_{41} — .62, .34; .96, .28	Mo_{42} — .61, .34; .95, .26	Tc_{43} — .60, .40; 1.01, .20	Ru_{44} — .62, .39; 1.01, .23	Rh_{45} — .69, .42; 1.11, .27	Pd_{46} — .76, .47; 1.23, .29	Ag_{47} — .69, .34; 1.03, .35	Cd_{48} — .64, .52; 1.17, .12	In_{49} — .53, .29; .82, .24	Sn_{50} — .66, .32; .98, .33	Sb_{51} — .74, .41; 1.15, .33	Te_{52} — .80, .36; 1.16, .44	I_{53} — .95, .38; 1.33, .57	Xe_{54} — .79, .71; 1.51, .08
Cs_{55} — .38, .19; .57, .19	Ba_{56} — .42, .27; .69, .15	La_{57} — .45, .26; .71, .20	Hf_{72} — .59, .32; .91, .27	Ta_{73} — .66, .36; 1.02, .29	W_{74} — .65, .39; 1.04, .26	Re_{75} — .66, .38; 1.04, .28	Os_{76} — .73, .40; 1.13, .33	Ir_{77} — .76, .41; 1.17, .35	Pt_{78} — .82, .42; 1.24, .41	Au_{79} — .82, .36; 1.18, .46	Hg_{80} — .73, .58; 1.31, .15	Tl_{81} — .56, .31; .88, .25	Pb_{82} — .63, .36; .99, .27	Bi_{83} — .65, .32; .97, .33	Po_{84} — .74, .33; 1.07, .41	At_{85} — .84, .33; 1.17, .52	Rn_{86} — .69, .62; 1.31, .08
Fr_{87} — .36, .19; .55, .18	Ra_{88} — .42, .30; .73, .12	Ac_{89} — .45, .23; .69, .22															

Lanthanide series	Ce_{58} — .45, .24; .69, .22	Pr_{59} — .46, .24; .70, .22	Nd_{60} — .46, .24; .70, .22	Pm_{61} — .47, .25; .71, .22	Sm_{62} — .47, .25; .72, .22	Eu_{63} — .50, .25; .75, .25	Gd_{64} — .50, .27; .77, .23	Tb_{65} — .49, .26; .75, .23	Dy_{66} — .50, .26; .76, .24	Ho_{67} — .51, .27; .77, .24	Er_{68} — .51, .27; .78, .24	Tm_{69} — .51, .28; .79, .23	Yb_{70} — .50, .33; .83, .17	Lu_{71} — .51, .27; .78, .24
Actinide series	Th_{90} — .50, .26; .77, .24	Pa_{91} — .49, .25; .74, .25	U_{92} — .50, .26; .76, .25											

TABLE II. PERIODIC TABLE $Z = N + 1/3$

electric charge is quantized, that is, why it comes in discrete chunks, a la the electron's charge. For many years this was the only explanation for that significant fact.

Repeated searches for magnetic monopoles have produced a few well-advertised candidates over the years but no evidence that could be confirmed by independent experiments. There is also a substantial body of astrophysical evidence against the existence of magnetic monopoles.

Several years ago some of the most popular theories of grand unification were found to absolutely require magnetic monopoles. These "GUT" theories link radioactivity to electricity and the nuclear force and give rise to the possibility of the radioactive decay of the proton. GUT monopoles were expected to be extremely heavy, with masses more than a million-billion times the proton mass. By particle standards the particles are complex, non-pointlike entities; almost a physics laboratory in themselves. Figure 2 is a schematic of one of these "GUT" monopoles, due to Rocky Kolb, a particle cosmologist at Fermilab. The paradox of the theoretical need for this monopole versus experimental facts (few, if any, monopoles in the universe) led to a drastic upheaval in modern cosmology that is still underway.

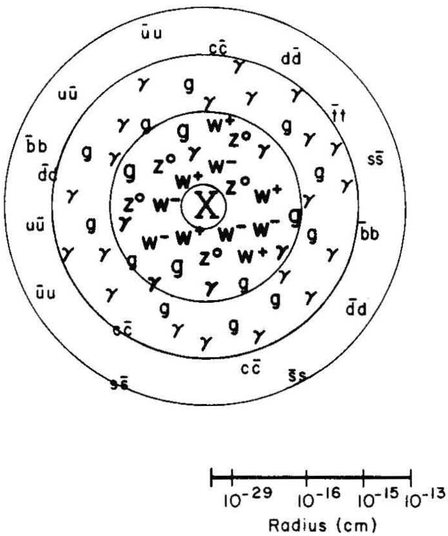

Fig. 2. Schematic of a GUT magnetic monopole. The complex character of this "elementary particle" is such that its internal workings are almost a laboratory of particle physics. (The illustration is due to Rocky Kolb of Fermilab.)

A subtle and interesting theoretical feature of monopole behavior surfaced in all this excitement. A monopole interacting with a proton would catalyze the proton decay, essentially converting the proton's mass into energy. The magnetic monopole exits the reaction unchanged. Not only that, but the interaction would happen quickly so that one monopole could generate substantial amounts of power.

Now it must be reiterated that no reproducible evidence for monopoles has ever been found and the weight of evidence from cosmology is that no very massive monopoles will be found! On the other hand, the ebb and flow of particle physics can uncover new results that are in stark contrast to prevailing dogma. With these caveats it is interesting to ask just where monopole catalysis could lead.

Magnetic monopole catalysis is somewhat different than either muon or quark catalysis. One is no longer fusing two hydrogen nuclei together to extract something like four percent of the mass equivalent in energy. Instead the monopole turns the proton into a quivering jelly of sub-atomic particles so that a fair fraction of the mass equivalent is available as energy (some part of the energy goes off as neutrinos that don't interact). How this catalysis could happen has been one of the more challenging puzzles of theoretical physics. It took years for the idea to be accepted and understood after it was first proposed by Callan and Rubakov. There is still some uncertainty about the rate at which it would occur but it is expected to be rather high. The cross section is velocity-dependent and increases as the monopoles slow down. Since there are no monopoles available to run tests on, one can't be sure at all of what one is talking about. The process might not work or there might be blind alleys similar to the situation with muon catalysis.

In any case one monopole can catalyze enormous numbers of protons and might provide about a milliwatt of power. (This number has already been calculated in astrophysical studies to set limits on monopole abundance in neutron stars. It is straightforward to scale it to earth-based densities.) A trillion monopoles could supply the power level of a gigawatt reactor while 10^{14} monopoles would catalyze a fair part of the U.S. power needs. This should be compared to the number of free quarks needed of about 10^{23}. On the other hand, the necessary free quarks would weigh only 1 gram while the monopole charge would weigh five to ten tons since the monopoles are expected to be very heavy.

A reactor could consist of a several-meter sphere of liquid hydrogen or water that would be boiled by the monopoles inside. The size would be set by the necessity for containing the products and energy from the proton decay. Ferromagnetic and paramagnetic container materials would have to be avoided because the monopoles would be attached by their image charges and stick to the surfaces (although they might continue to catalyze and burn holes in the container). Some sort of focusing might be needed to keep the monopoles in the container. Here gravity could help. Unless something was done the monopoles would probably fall to the center of the earth because of their mass and small diameter. A properly shaped upward pointing magnetic field might help to contain one polarity.

Once again, no monopoles have been found. An obvious place to search for magnetic monopoles is an iron mine where a monopole might stick in the iron ore in the same way iron filings stick to a magnet. Searches of iron for monopoles have so far been fruitless.

Even if free massive monopoles were found they would be extremely hard to stop because of their very large momentum. In fact, they could easily go through the moon without stopping.

Since neither magnetic monopoles nor free quarks have been found, all of this might be considered a flight of science fiction. Indeed years ago, before the enormous wave of interest in monopoles, I published a science fiction novel with my wife, "Minotaur in a Mushroom Maze", in which magnetic monopoles were used to generate power by catalysis. GUT monopoles were only a gleam in a young theorist's eyes (G. 't Hooft) at the time so there was no hint of true monopole catalysis and the process had to proceed via hydrogen fusion. Figure 3 is the illustration of the catalysis device as it appeared in <u>Analog</u>. All of this was combined with a blood-thirsty lot of middle eastern fundamentalists, stock market manipulations, and ferocious pitbulls. Publication provided the down payment on a Pinto, not a Porsche, perhaps because this was not wild enough science fantasy.

The point is monopoles and free quarks are not science fantasy. Instead they represent visualizations of science as it might be. There is a vast difference between a novel such as M^3 and a sophisticated scientific paper like 't Hooft's. Such a paper can posit principles that mesh with existing

Fig. 3. Monopole catalysis vessel as it appeared in the pages of Analog in 1976.

theories and then reach way beyond to suggest astounding new ideas. Even the originator of the theory may not have any sense of how far his idea may carry. Figure 4 reproduces a letter from 't Hooft written to me in 1975 a short time after his theory was published. At that point he thought his monopoles would only exist in "a rather small subclass of possible weak interaction theories." Within a year or so the picture had changed and the absence of super heavy monopoles was becoming a gnawing problem. Ultimately an entirely new picture of the cosmos, the inflationary universe, was needed to solve the embarrassment of the missing monopoles. That picture explained the homogeneous nature of the universe for the first time.

Monopole or quark catalysis certainly will not be the first real application of particle physics. Several years ago

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TRAJECT: ad RHENUM

April 25, 1975

Dear Dr. Carrigan,

Thank you for your letter of March 25. I am happy with your interest in my paper on monopoles, and with your attempts to detect these experimentally. My monopoles, however, (which would only exist in a rather small subclass of possible weak interaction theories) are in any case extremely heavy and I fear that even if the necessary energy would be available, the pair production cross section would be embarrassingly small. Like e^{-137} or $e^{-\sqrt{137}}$ or so. I'm also pessimistic about magnetic monopole quark theories. They do not explain the triality condition of quark confinement. Quarks could be non-Abelian monopoles but that has nothing to do with ordinary magnetism.

Of course I do not want to discourage you with searches, but personally I think that if monopoles exist the best chance to find them is to look for them in oysters, or the North Pole or Antarctica, etc.

Sincerely,

G. 't Hooft

Fig. 4. Transcription of a letter from G. 't Hooft shortly before his theory started the modern monopole craze.

the same might have been said of muon catalysis. The remarkable developments at Los Alamos by Jones and his colleagues lowered the betting odds on muon catalysis so one can no longer blindly bet against muon catalysis eventually being practical.

Much more likely is that some new facet of physics will be uncovered with unexpected and interesting applications. Remember the muon itself was entirely unexpected. Nuclear fission is almost an accidental artifact. Modern quantum mechanics was discovered sixty years ago and has since yielded such history-shaking developments as the transistor and the laser. Could it be that a new particle would be discovered at the Superconducting Super Collider that was able to catalyze fusion easily? We'll never know unless we try!