Muon Catalysed Fusion

Nuclear confinement by chemical bonding within muonic molecules

P. Froelich, Uppsala

(Quantum Chemistry Institute)

We are presently witnessing an exciting scientific and technological race towards energy production *via* nuclear fusion, between physicists attempting to achieve extreme conditions and chemists trying to arrive at the same results by more subtle means. Fusion reactions can be spontaneously catalysed by negative muons in a cold mixture of tritium and deuterium, through the formation of muonic molecules dtμ.* These molecules are held together by muons instead of electrons, and because muons are 207 times heavier than electrons, they are some 200 times smaller than their ordinary counterparts and have very high vibrational energy. Their constituent nuclei can overcome the repulsive Coulomb barrier by tunnelling and enter the strong force interaction range. After the fusion event, the muon becomes free, and can continue to catalyse new fusions, each releasing 17.6 MeV energy. Because the muon can be reused, it can trigger a release of energy which greatly exceeds its own rest mass!

Because muons are not inexpensive particles, the basic questions is: how many fusions can one muon create during its short life time of two microseconds? Obviously, this depends on the formation rate of dtμ, or, since this is not a one step process, on a series of microscopic reaction rates which jointly determine the time between consecutive fusions.

Muon catalysed fusion was first observed in hydrogen bubble chamber experiments at Berkeley in 1957. It was originally disregarded as a possible source of energy gain, owing to an underestimation of the formation rate of the muonic molecules. No more than one or two fusions per muon were expected. The recent growth of interest in this field is due to the theoretical prediction, made by Russian scientists in 1977, of a high resonant formation rate of dtμ molecules ($\lambda_{dt\mu} > 10^8$/s at liquid hydrogen density (LHD).

This prediction brought the subject into experimental focus, and surprisingly high fusion yields were discovered — even exceeding those predicted by theory. Today, experiments probing various aspects of μCF are being conducted at the Los Alamos Meson Physics Laboratory (LAMPF), the Paul Scherrer Institute (PSI, formerly SIN) in Switzerland, in Gatchina and Dubna in the USSR, at The Japanese National High Energy Physics Laboratory (KEK), the Rutherford-Appleton Laboratory (RAL) in England, and the Tri-Universities Meson Physics Facility (TRIUMF) in Canada. As many as 150 fusions per muon have now been obtained, reviving hopes that an energy gain may be possible. The scale of interest in muon catalysed fusion is reflected by the frequent international conferences (Tokyo 1986, Leningrad 1987, Sanibel Island 1988). A new professional journal has been created to become the forum for the very rapid development, and an official agreement on US/USSR cooperation has been signed.

The aim of present on-going research is to understand, qualitatively and quantitatively, the series of microscopic events constituting the fusion chain, together with their dependence on the macroscopic conditions of temperature, fuel density and/or composition. The ultimate goal is to optimize the fusion yield and to explore the suitability of muonic catalysis for energy production.

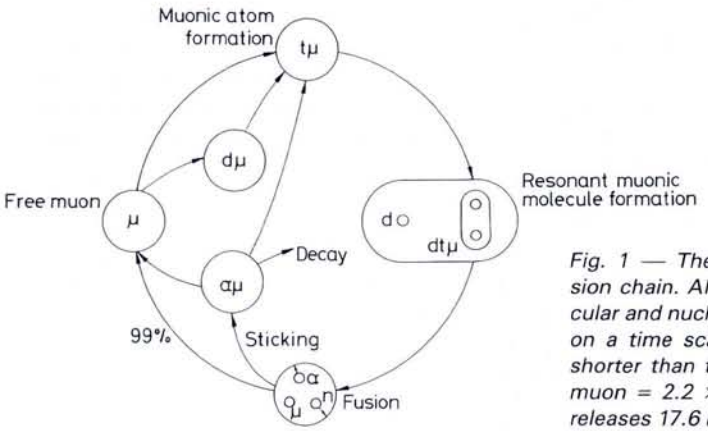

Fig. 1 — The mesocatalytic fusion chain. All the atomic, molecular and nuclear reactions occur on a time scale which is much shorter than the life time of the muon = 2.2 × 10⁻⁶ s. Each cycle releases 17.6 MeV energy.

FUSION CHAIN

The fusion chain is schematically displayed in Fig. 1:

1. Formation of muonic atoms

When a short-lived muon enters the deuterium-tritium mixture, the race against time begins. In less than a nanosecond muonic dμ or tμ atoms are formed

$$\mu + D \rightarrow d\mu + e \qquad (1)$$

This process includes: slowing down the muon, its capture into high levels of the muonic atom, and the cascade to the ground state. If the muon first forms a dμ atom, it is likely to transfer to the heavier triton, since the binding energy of tμ (2711 eV) exceeds that of the dμ atom (2663 eV).

$$d\mu + t \rightarrow t\mu + d \qquad (2)$$

2. Formation of Muonic Molecules

During collisions with D_2, T_2 or DT molecules, the tμ atom behaves as a heavy neutron, because it is electrically neutral, very tightly bound (regarding collisions with electrons) and very small compared with electronic molecules. This is why it can penetrate the host molecule without breaking its electronic shell, and make a close collision with the deuterium nucleus. During such a collision, a muonic molecule may be formed, provided the right kinematical conditions are met. In this respect two basic formation mechanisms are distinguished. In the *direct process* (see Fig. 2), the binding energy of newly formed molecu-

* In the following, lower case letters are used for particles and upper case for normal atoms.

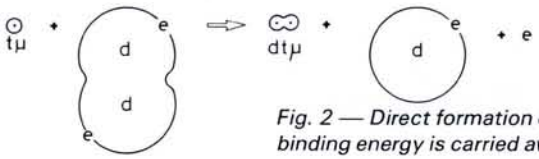

Fig. 2 — Direct formation of dtμ in D_2-tμ collision. The released binding energy is carried away by an electron.

les is released through dissociative ionization of the D_2 molecule

$$t\mu + D_2 \rightarrow dt\mu + D + e \qquad (3)$$

This process is not very efficient, which was the reason for the rejection of muon catalysed fusion as a possible energy source in the early days of its history.

It was the discovery of the so-called resonant mechanism that renewed interest in dtμ fusion. In the *resonant process* the binding energy of dtμ is released *via* excitation of rotational and vibrational levels of the hosting electronic molecule (see Fig. 3). The host molecule stays intact, while the intrinsic dtμ acts as one of the nuclei

$$t\mu + D_2 \rightarrow < (dt\mu)dee > \qquad (4)$$

The resonance condition involves the proper energetic balance between the kinetic energy E_T of the colliding tμ and D_2, the excitation energy of the molecular complex [(dtμ)dee], and the binding energy E_b of the intrinsic dtμ:

$$E_T = E_{exc} - E_b \qquad (5)$$

where the excitation energy E_{exc} is with respect to the ground state of the D_2 molecule:

$$E_{exc} = E^{(dt\mu)dee}_{(J=1,\,v=2)} - E^{D_2}_{(J=0,\,v=0)} \qquad (6)$$

The resonance condition for the formation process is illustrated in Fig. 4.

It is clear from the above condition that the resonance formation strongly depends upon the existence of a loosely bound state of dtμ, which has a binding energy smaller than the dissociation energy of D_2 ($\cong$ 4.5 eV). Indeed, careful calculations of the mesomolecular spectrum indicate the existence of such a state with a binding energy $E_b^{(J=1,\,v=1)}$ = 0.66 eV, which is remarkably fortuitous considering the very sparse distribution of mesomolecular energy levels. Thus, the resonant process can only occur at a well defined thermal energy E_T, and this determines the optimal temperature for the fusion process.

New theories predict that several resonances participate in the formation process, and the optimal temperature has been estimated to be $T \cong$ 1800 K. The most recent developments indicate that the dtμ molecules may also be formed by three body collisions of the type tμ + d + X → dtμ + X', where the third body X can be an electron, a nucleon, or a neutral atom. Fusion efficiency is very sensitive to the details of the molecular structure which makes it necessary to determine, for instance, the energy levels of dtμ to an accuracy of meV in 3 keV of binding energy: a challenging theoretical and computational problem which has been resolved by quantum chemists.

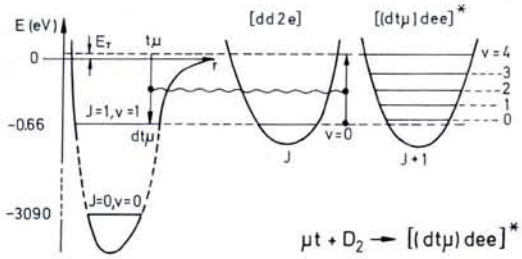

Fig. 4 — The resonant condition for dtμ formation. From the left, potential wells and energy levels of: dtμ, D_2, and < (dtμ)dee > on the common energy scale of D_2-tμ collision.

3. Fusion Process

One the muonic molecule is formed (in its rovibrational excited state) it can quickly (within 10^{-10} s) de-excite to the ground state, where fusion is most efficient.

Mesocatalytic fusion is one of the most spectacular manifestations of the quantum tunnelling effect. The muon binds the nuclei in a very small volume (equilibrium distance R_0 is about 5 × 10^{-15} m) where they have a very high vibronic energy (ground state vibrational energy $E_v$ib is some 250 eV). Muonic binding produces local plasma conditions, but on a microscopic scale. To appreciate the role of this *chemical confinement* one ought to observe that the corresponding plasma conditions would need a density of $\rho = (1/R_0)^3 \cong 10^8$ LHD and a temperature $T = E_{vib}/k \cong 10^6$ K, as in the interior of stars!

Under such conditions, penetration of the Coulomb barrier between the nuclei by tunnelling is very likely. In less than a picosecond, the nuclei are brought into the strong force interaction range, fuse *via* the nuclear reaction, and release the energy in the subsequent decay of the compound nucleus (see Fig. 5):

$$(dt\mu) \rightarrow (^5He)\mu \rightarrow \alpha + \mu + n + 17.6\ MeV \qquad (7)$$

Formation of the $^5He^{(3/2^+)}$ compound nucleus is facilitated by the $J^\pi = 3/2^+$ nuclear resonance in the inelastic d-t scattering channel. The energy of the relative d-t motion in the muon induced fusion is situated on the shoulder of the resonant d-t cross-section, see Fig. 6.

One can thus say that the muon induced d-t fusion proceeds "in the shadow" of the strong nuclear resonance. The exact influence of this resonance (and of strong nuclear forces in general) on μCF parameters is a hot subject of current theoretical research. Inclusion of the strong forces in the Coulomb description of the dtμ molecule turns its bound states into resonances; the dtμ decays *via* fusion, and its life time dictates the fusion rate. The essence of the problem is how to include the information from the *nuclear two-body* (d-t) *scattering* problem into the *Coulomb three-body structure* problem of dtμ.

4. Muon Sticking and Reactivation

After a fusion event, the muon is generally available for the next catalytic process, except when it binds to the α particle, thus being removed from the fusion reaction chain (see Fig. 1)

$$dt\mu \rightarrow (^5He)\mu \rightarrow \alpha\mu + n + 17.6\ MeV \qquad (8)$$

The probability ω_0 that the muon will be bound to the α particle is given by the branching ratio between the two and three body fragmentation of the fusing $(^5He)\mu$ system and is referred to as the *initial sticking fraction*.

Fortunately, part of the muons bound to the α particle are returned to the fusion chain by means of collisional detatchment (*via* muon ionization αμ + d → α + d + μ, or muon transfer αμ + d → α + dμ) when the αμ slows down in the fuel mixture. These stripping reactions counteract the sticking, and so an effective sticking coefficient ω_{eff} can be introduced.

The sticking probability is less then 1%, yet it appears to be the bottle-neck in the fusion chain. Indeed, the simplified fusion yield is given by

$$Y = \lambda_c/(\lambda_0 + \lambda_c\,\omega_{eff}) \qquad (9)$$

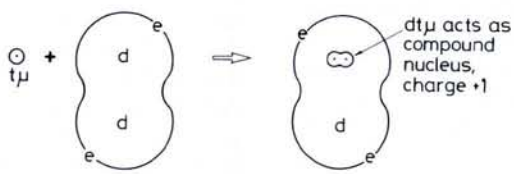

Fig. 3 — Resonant formation of dtμ in D_2-tμ collision. The dtμ binding energy is transferred to the ro-vibrational motion of the hybridized hosting molecule.

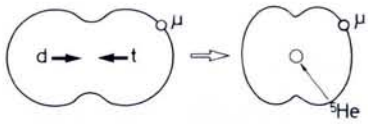

Fig. 5 — Fusion by chemical confinement within the dtμ molecule. At the instant of nuclear reaction, the molecular orbital of dtμ resembles the atomic orbital of (^{5}He)μ.

where λ_0 is the muon decay rate (inverse of its life-time) and λ_c is the muon cycling rate (inverse average time between the consecutive fusions, determined mostly by the slowest process, namely the dtμ formation rate). This simplified expression reveals the role of the sticking fraction; it defines the ultimate limitation to the number of fusions per muon, as the cycling rate increases.

The experimental value for the effective sticking fraction, obtained independently of the fusion neutron disappearance rate is between 0.5 and 0.3% at the density 1.2 LHD. New experiments based on the direct detection of αμ ions are under way in the form of joint ventures by RAL/LAMPF, and PSI/Gatchina. The current theoretical value of the initial sticking factor (obtained by means of three-body quantum chemical calculations) is 0.886%. The main thrust of the research is to find a way to enhance the reactivation and lower the sticking fraction.

PROSPECTS OF ENERGY PRODUCTION

The principle of μCF is the same as that of a typical chemical catalysis:

$$E_{in} + d + t + \mu \rightarrow dt\mu \rightarrow \alpha + \mu + n + E_{out} \quad (10)$$

The remarkable reaction above occurs without any extra energy input, except the one needed for the production of muons (E_{in} is an energy of thermal motion, in the range of meV). If E_μ denotes the energy needed for muon production, and Y the neutron yield per muon, the condition for (scientific) energy break-even is

$$E_\mu < E_{out} = Y \times 17.6\,\text{MeV} \quad (12)$$

It is clear that the key questions regarding possible energy production are: 1) can muons be produced cheaply, and 2) how many fusions can one muon promote during its short life time?

Recent experiments at LAMPF have demonstrated yields of 150 fusions/muon, with energy liberation just short of 3 GeV/muon, and with indications that yields of some 300 fusions/muon might be possible.

As to the cost of muons the current estimation is some 5 GeV in beam power per muon, although the theoretical limit is below 2 GeV. Present muon factories are far from the optimal efficiency.

Along with the progress in theoretical and experimental research, different concepts of muon-catalysed fusion reactors are being developed. Pure fusion design is not possible today, but fusion-fission hybrids combined with a spallation breeder would require only some 100 fusions/muon, and could be operated with a net energy gain even if the cost of a muon stays as high as 5 GeV. Recent conceptual systems envision sidestepping the production of intermediate pion and muon beams. In these so called synergetic systems the D/T mixture plays the role of both the target for muon production and the fuel for μCF.

Finally, some safety considerations ought to be mentioned. Needless to say, thermal runaway of the muon catalysed fusion is not possible due to the self-limiting nature of the process at high temperatures. Since the muon catalysed fusion is a sort of resonant chemical reaction, the process is expected to proceed effectively only at the corresponding resonant temperature.

The process is still in an early stage of exploration. Only future research will show whether its efficiency is irrevocably given by Nature, or may be altered by scientific and technological progress.

REFERENCES

Further introductory reading can be found in:

Rafelski J. and Jones S.E., *Sci. Amer.* **257** (1987) 1, 84.

Ponomarev L.I. and Fiorentini G., *Muon Catalysed Fusion* **1** (1987) 3.

Jones S.E., *Nature* **321** (1986) 127.

Bracci L. and Fiorentini G., *Physics Reports* **86** (1982) 171.

Gershtein *et al.*, *Sov. Phys. JETP* **53** (1981) 872.

Petrov Y.V., *Nature* **285** (1980) 466.

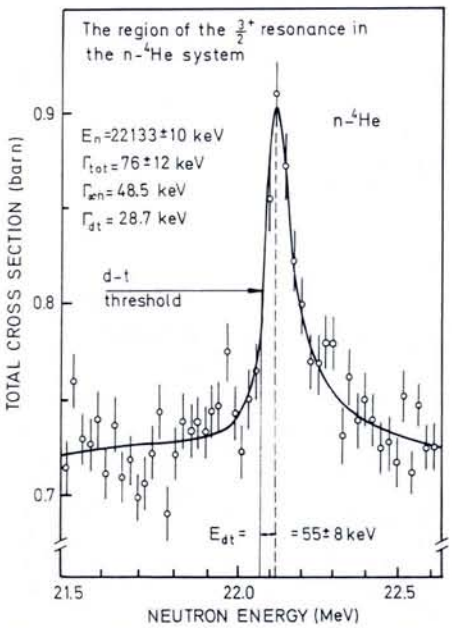

Fig. 6 — Cross-section for the n-α scattering in the vicinity of 3/2⁺ resonance, with the energy above the d-t threshold and the total width estimated to be E_{res} = 55 keV and Γ_{tot} = 76 keV, respectively.

The Case of the Non-Stick Pan

It is becoming ever more probable that when all the conditions are carefully controlled, the electrolysis of D_2O using a palladium cathode, will yield no energy gain and a negligible number of neutrons. So the table-top fusion reactor [1] is not for tomorrow. Both Cal. Tech. and MIT have failed to find any of the positive effects reported by Fleischmann and Pons [2] or even Jones *et al.* [3]. At Harwell, where they have had 30 cells running since 10 March (some of which were set up in collaboration with Fleischmann) no heat gain or neutrons had been detected by the end of April. Again in EPFL Lausanne, nothing. So what do we conclude?

It is a little early to be 100% certain, but then absolute certainty in science is rather rare. However certain deficiencies have been noted in the reported Pons, Fleischmann experiments (which were run on a shoestring), notably the emergence of the cathode from the electrolyte and the relative primitive techniques used to measure the neutrons and monitor the background. Surface effects at the electrode are sufficient to explain the apparent calorimetric gain, tritium is a familiar contaminant and a variety of mechanisms have been invoked to account for the seemingly excess neutrons, ranging from radon emission in the laboratory to high electric fields generated in the lattice — a sort of micro piezoelectric effect [4].

The moral to the story which should be pointed out to the lay man and the politicians, is not that individual scientists may be fallible, which we know, but that the establishment can be relied on to get it right in the end. Moreover the establishment is not so arrogant that it declines to examine something new when it comes along.

REFERENCES

[1] Shaw E.N., Electro-chemical Induced Fusion, *Europhys. News* **20** (1989) 45.

[2] Fleischmann M. and Pons S., 'Electrochemically Induced Nuclear Fusion of Deuterium', *J. Electroanal. Chem.* **261** (1989) 301.

[3] Jones S.E. *et al.*, 'Observation of Cold Nuclear Fusion in Condensed Matter', *Nature* **338** (1989) 737.

[4] Klyuev V.A. *et al.*, 'High-energy Processes Accompanying the Fracture of Solids', *Pis'ma Tekh. Fiz.* **12** (1986) 1333.