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Muon catalysed fusion—the present status

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Abstract : This article reviews the present status of the challenging field of muon catalysed fusion, by which fusion of light nuclei can be catalysed at low temperatures by muon binding. The study of this intriguing phenomenon encompasses different disciplines of physics, including particle, nuclear, atomic, molecular, accelerator and reactor physics. Starting with the intrinsic characteristics of the muon, the review highlights the physics of the negative muon in matter that culminates in the fusion act. The post-fusion scenario and the dynamics of the reactions and associated physics are considered. In part II, the applicational and utilisation prospects and experimental status are discussed.

Keywords : Muons, exotic atoms and molecules, nuclear fusion.

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PART I : The Physics of the Process

1. Preliminaries

Nuclear energy liberated during the fusion of light nuclei into heavier ones provides the driving power of the Cosmos. Stars are ignited as light hydrogenic nuclei start to collide closely and fuse and their life cycles are controlled by the rate and amount of burning fuel. Even a modest star like our sun churns out enough energy to support life on one of its planets through the millenniums. While mankind has succeeded in harnessing nuclear energy from fission of heavy nuclei, practical utilisation of fusion energy still eludes us. Since fusion fuel is readily available, is more energy efficient, and promises cleaner burning we still crave its utilisation.

The road to fusion energy is, however, tough and trying. Conventional research for utilisation of fusion energy relies on attainment of collossal temperatures where the atoms and molecules of the hydrogenic fuel dissociate. In such a state of matter, called the plasma state, the bare nuclei, stripped off their electronic dressings, collide at energies large enough to overcome the repulsive Coulomb barrier between each other that arises because of their like positive charges. The requirement of these high temperatures is dictated by the need to accelerate the fusing nuclei to energies sufficient to cross this repulsive Coulomb barrier. During the close collisions the nuclei fuse together releasing the much sought energy*. This kind of fusion technology involves generally powerful lasers, huge magnets and plasmas at forbidding temperatures, and still remains way above utilisation threshold.

Nature provides however, a more subtle means of achieving fusion without necessitating recourse to these formidable plasma temperatures and their associated containment problems, (although this has its own quota of problems). The principles of quantum mechanics allow the nuclei to defy the dictates of classical physics and to tunnel through the Coulomb barrier without having to jump over it. This kind of sub-barrier fusion can occur at energies far below the barrier height

*When two light nuclei fuse, the total mass of the initial nuclei exceeds that of the final nuclei and this 'mass defect' is converted into energy. e.g. $t+d \rightarrow \alpha+n+17.6$ Mev.

but unfortunately has a very low probability for nuclei at normal separations in atoms and molecules. Under certain conducive conditions the probabilities of sub-barrier fusion can be heightened considerably and cold fusion can be put on observation threshold.

Muon catalysed fusion is an established manifestation of this kind of sub-barrier cold fusion. The physics is elegantly simple. By virtue of its large mass and negative charge, the muon can confine two electro-repulsive light nuclei within muonic molecular dimensions of $\sim 10^{-11}$ cm. At this close proximity the nuclei aquire a high probability of sub-barrier fusion and fusion rapidly ensures. For the d-t system, a single muon can catalyse well over 100 fusions. We unfold through this review the different aspects and intricacies of this intriguing phenomenon including the utilisation prospects (We do not deal with the recent reports of amuonic cold fusion in deuterated metals). This review is aimed at self containment for the general physics reader so the specialised details are confined in different sections for those interested in specific sections of the interdisciplinary physics. The first section introduces the enigmatic muon to those unfamiliar with its characteristics. Subsequently, the story of a negative muon in matter is developed, culminating in the fusion act. The muon's electromagnetic slowing down, continuum to bound transitions, formation and stabilisation of fusion hosting muomolecules, the physics and dynamics of the fusion channels, the post fusion muon fate and the cycle rate comprise the associated physics. The experimental scenario and the energy utilisation status are discussed in the final sections.

2. *Introducing the muon*

The muon is a spin half elementary particle that comes in both positive and negative charge states, and has a lifetime of 2.2×10^{-6} sec. But this microsecond lifetime is sufficient to allow it to generate varied and 'exotic' activities in matter.

Belonging to the class of particles called leptons, because it responds to electroweak forces only and is inert to strong interaction signals, the muon (μ), along with its leptonic partner the muon-neutrino (ν_μ), forms the second generation lepton doublet. This corresponds to the second generation flavour doublet of *c* and *s* quarks. The (e, ν_e) and (τ, ν_τ) make up the first and third generation lepton doublets. Because of its half integral spin, the muon obeys Fermi Statistics and falls in the fermion classification.

The muon was discovered in Cosmic Ray experiments (Anderson and Neddermyer 1937, Street and Stevenson 1937). Being intermediate in mass between the electron and proton, it was identified with the pi-meson, the particle hypothesised to be the carrier of nuclear forces. However, it was soon found that this particle did not react violently with nuclei as would expected if it was a pi-meson. Subsequently, the pi-meson was found and the earlier particle christened the mu-meson.

The mu-meson, as it was then called, was found to be a particle exactly like the electron – except for its much larger mass. It caused much confusion at the time for no one could understand Nature's need for a heavy electron, and it was described as 'the unwanted baby left on the doorstep' (Gellman et *al* 1957). Today, with the advent of lepton and quark generations, the muon has its natural place in the hierarchy of particles. Further, it is now well-known that it can lay no claim to the 'meson' tagged to its name, as it is neither a strongly interacting particle nor an integral spin particle – both requisites for the 'meson' nomenclature. Unfortunately the literature continues with its random use of the term 'mu-meson' for this lepton with fermionic properties, and these should be read as 'muon' for correctness.

The opposite charges dictate different electromagnetic characteristics for the positive and negative muon. Thus while the negative muon behaves in matter like a heavy electron, the positive muon is of prime importance in μSR studies and solid state physics. In this work, however, we do not concern ourselves with the positive muon but concentrate on the negative muon. Negative muons are obtained most efficiently from pion decay according to $\pi^- \rightarrow \mu^- + \nu_\mu$ and the parent pions are produced in high energy nuclear collisions (c.f. part II, Sec. 3). Negative muons decay purely by the leptonic mode $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$.

While muons are the most abundant component of the sea level cosmic ray flux, their number is still far too low for high precision research. Specialised muon catalysed fusion experiments are, therefore, performed at accelerator centres where dedicated muon beams are produced for research purposes. These muon 'factories' are located in different institutes all over the world, such as Lampf, and others in USA, Triumpf in Canada, KEK in Japan, RAL at UK, PSI in Switzerland and LNPI and others in USSR.

3. *The negative muon in matter*

The story of a negative muon in matter is a complex mixture of many processes. Numerous collisions and interactions gradually de-energise and slow the muon to thermal velocities. After thermalisation, muons are captured into Coulomb bound states. Such muonic atoms and molecules are often called 'exotic' atoms and molecules for their muon flavour. The details of the continuum to bound state transition will be discussed in Section 4. The muon's electromagnetic capture results rapidly in a ground state muonic atom. In this state the muon's life is jeopardised by the possibilities of decaying by weak interaction into an electron and two neutrinos, or of being swallowed – by its host nucleus in a weak capture process.

Alternatively, this entity – the muonic ground state atom can join with another nucleus to form a muonic molecule. For some hydrogenic isotopes, this is the most dominant channel.

We restrict ourselves to hydrogenic media only as this is relevant for muon catalysed fusion, and show the many possible channels in Figure 1. Muonic molecule formation can occur by two mechanisms and these have important

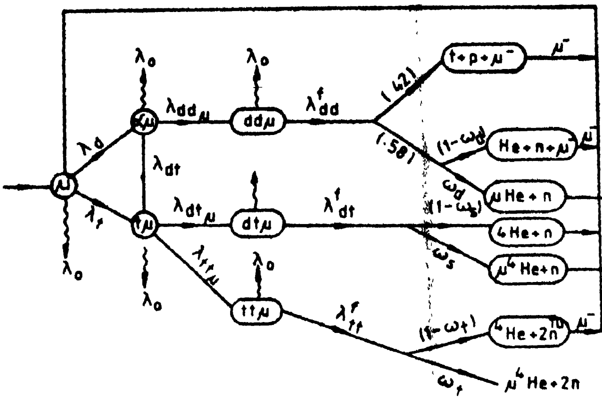

Figure I. Muonic processes in hydrogenic target.

consequences for the total fusion rate. These features are discussed in Sections 7 and 8, along with the isotopic preferences, back decay, the transfer reactions, stabilisation of the molecule and hyper fine effects.

Once the stabilised muomolecule is formed, fusion is rapid, and in most cases the post-fusion scene finds the muon free to catalyse further fusions. The released muon repeats the cycle of slowing down and being captured into atomic states. Finally, molecules are again formed and the next fusion event catalysed. This catalysis chain can continue until the muon is lost by inevitable weak decay process* or by being electromagnetically bound into an atomic state about the charged helium isotopes produced in the fusion. The latter loss is referred to as 'sticking' and its study forms a large part of muon catalysed fusion research. Sticking and its reduction are discussed in Section 11.

As the experimentally observed neutron yields depend on the different competing channels, the analysis of the data is a complex involvement of many parameters unless certain simplifying assumptions can be made.

The *d*-t isotopic combination is the most conducive for efficient muon catalysed fusion, due to the favourable combination of high $dt\mu$ molecule formation rate, high *d*-t fusion rate from the muonic molecule and the comparatively low post-fusion sticking. This tripple blessing singles out this system as the most sought after and studied for possible utilisation aims.

In the analysis of the fusion cycle for a *D-T* mixture, one usually assumes a steady state (Jones *et al* 1986, 1983) and at *LHD*, we can write

$$\frac{1}{Y_n} = \frac{\lambda_0}{\lambda_c} + W \tag{3.1}$$

*Weak Capture rate is very much smaller in hydrogenic media.

where

Y_n is the average number of fusions per muon,

$\lambda_0 = 0.455 \times 10^6$ s^{-1} is the free muon decay rate,

λ_c is the muon cycling rate,

and

W is the fractional loss per cycle and includes that due to scavenging by impurities, although it is dominated by 'sticking'.

Both the muon atomic capture (see Sec. 4) and the fusion processes (see Sec. 9), are very fast, and generally the cycling rates can be written in the simplified form

$$1/\lambda_c = \frac{q_{1s} C_d}{\lambda_{dt} C_t} + \frac{1}{\lambda_{dt\mu} C_d} \tag{3.2}$$

where C_d and C_t are the deuterium and tritum concentrations, λ_{dt} is the ground d to t transfer rate, $\lambda_{dt\mu}$ the molecule formation rate and q_{1s} is the probability of $(d\mu)$ reaching its ground state from the excited state in which it is formed (cf Sec. 5).

The experimental features are discussed in Part II. Collisional muon catalysed fusion has a much lower probability than from the molecular state (Chatterjee and Das 1991).

Before closing this section a brief glance at the historical highlights would be appropriate. The intriguing idea that negative mouns might be able to catalyse fusion of hydrogenic nuclei was suggested by Frank (1947) and the physics analysed by Sakharov (1948). Zeldovich (1954) also discussed the process. Subsequently, during an experiment with a K^- beam at Berkeley, Alvarez and his co-workers (Alvarez 1957) observed some strange events in the Bubble Chamber signatures. Independent of the earlier theoretical work, these events were correctly interpreted and identified as muon catalysed fusion events. An exhaustive theoretical treatise by Jackson (1957), predicted the rates of the different processes comprising the phenomenon. However, the feasibility of its use as a potential energy source was found negligible in this and other papers at the time. The '57 to '60 period witnessed the first generation muon catalysed fusion experiments, mostly in bubble chambers (Bracci and Fiorentini 1982).

Continued research through the seventies by the USSR scientists kept alive the subject of muon catalysed fusion on the theoretical and experimental fronts. Thus Ponomarev and his co-workers developed the Adiabatic basis set to obtain accurate values for the energy levels of the muonic molecules (Ponomarev and Vinitsky 1979), and performed exhaustive calculations on the different reactions of the catalysis cycle. The weakly bound molecular levels and the fascinating mechanism of 'resonant molecule formation' (Vesman 1967), (see Sec. 7) were discovered in this period and triggered the new generation experiments. The Los Alamos (Jones et *al* 1983) experiments yielded the startling result that a single muon could catalyse about a hundred fusion, contrary to earlier pessimistic predictions. This revived hopes for its utilisation.

Today *μcf* research has crystalysed into one of the front line research fields both for its application potential and the fascinating interdisciplinary physics it encompasses.

4. *Continuum to bound state transitions*

The negative muon entering matter is slowed down by collisions with the host particles. This process naturally depends both on the density of the target and the energy of the muon and has been studied by different methods.

The main channels of energy loss are by ionisation and excitation of the electrons in the medium. For solid targets the electrons are treated as a Fermi Gas and the inelastic collision cross sections and resulting energy losses estimated by classical approach. The 'Fermi Teller Law' predicts the slowing down time, from few KeV to thermalisation to be $\sim 10^{-14}$ sec, and the subsequent capture to bound state to be proportional to the atomic number z of the capturing nucleus (Fermi and Teller 1947).

Several computations of the continuum to bound state capture have been carried out (for e.g. Wightman 1950, Haff and Tombrello 1974, Leon and Bethe 1962, Daniel 1976, Schnewly et *al* 1978, Cohen 1983, Garcia et *al* 1987, Korenman and Popov 1989, Chatterjee 1986 and others).

In general, the Auger mode of capture is found to dominate and the muon is captured into a high 'n' orbit ($n \sim 14$), that overlaps strongly the orbit of the ejected electron. The papers referred also probe the details of the capture, the chemical effects and the molecular and atomic nature of the captured muon states. Different approaches including the classical trajectory Monte Carlo method (Cohen 1983), the time dependent Hartree Fock theory (Garcia et *al* 1987), and classical quantal coupling (Kwong et *al* 1987) have been used to compute the Auger capture of slow muons.

Radiative capture can populate the more stable, deeply bound muonic orbits as opposed to population of outer levels by Auger capture. However, their cross sections are small compared to the Auger process.

Despite the large amount of theoretical work, complete compatibility with experiment has not been achieved, nor an exact comprehensive theory describing the entire capture process.

Experimental data on the direct Coulomb capture is not prolific, particularly regarding the details of the capture channels and rates. Auger electrons have been observed by Fry (1951) and others. Experimental results on pion capture (Aniol et *al* 1983) also yield information on muon capture. X-rays from radiative transitions have been measured (Chang 1949, Hincks 1951).

The high precision data now available for the pivotal μcf parameters provokes better understanding of this initiating section of the cycle, although it is too fast to significantly affect the fusion yield.

The velocity distributions of the muonic atoms and possibly the q_{1s} problem too are related to the capture details and these issues are important for μcf studies.

Recent experiments report also interesting deviations from expectations for muonic atoms processes, some of which could be related to the capture (Kottman 1990, Mulhauser *et al* 1990, Kraiman *et al* 1990). Theoretically too the problem is not closed.

5. *Cascade and stabilisation of muonic atoms*

In the last section we left the muon predominantly in an excited $n \sim 14$ orbit about one of the hydrogenic nuclei present in the target. From this state it rapidly cascades to the ground muonic orbit. The early stages of this cascade proceed by ejection of neighbouring electrons as the energy release is too slow to favour photon emission. Cascade through the inner orbits, however, proceeds in general by photon emission. This is favoured by the larger available energy and by the scarcity of electrons close to the nucleus.

The radiative and auger cascade rates have been computed by different workers and generally require elaborate computer codes (Vogel 1975, Eiesenberg and Kessler 1961 and others). The whole cascade is estimated to be over in times which are again fast compared to the rates that control the catalysis cycle.

It is interesting to conceive the spatial collapse of the muonic atom with the progress of the cascade. The initial muonic atom in $n \sim 14$ state, with dimensions of ordinary hydrogen atoms starts the cascade. Since the muon is 206 times more massive than the electron, the stable ground state of the muonic atom is smaller than the electronic first Bohr orbit by this factor of 206. Ground state muonic atoms are therefore shrunk 200 times compared to their electronic counterparts. The stabilisation of the muonic atom then corresponds to a spatial shrinking of the system with each step of the ensuing cascade.

Apart from its dramatic consequence, for muon catalysed fusion, the smallness of the stable muonic atom gives rise to other interesting physics. Photons emitted in low level muonic transitions lie in the X-ray range and as these inner orbits have a large overlap with the nucleus they can provide accurate information on nuclear properties. Parity violating effects are also expected to be cleaner in muonic atoms.

The isotopic effects determine the overall channel probabilities. At any stage the experimental vessel usually has atleast more than one hydrogenic nuclear species. Then transfer from the lighter to heavier nucleus is an irreversable process at thermal energies.

The transfer reaction $$d\mu(n)+t \rightarrow t\mu(n)+d+\frac{48}{n^2}\ \text{eV} \qquad (5.1)$$

(*n* corresponds to the atom level)

can compete with the deexcitation rates for $d\mu$ (Menshikov and Ponomarev 1986). The ground state transfer has a rate $\sim 10^8 \text{ sec}^{-1}$.

The probability $q_{1s} < 1$ for the d_μ to reach its ground state is an important factor for μcf as d to t transfer of muon is suppressed for the ground (d_μ) state. There appears to be some disagreement between theory and the experimental estimates of this parameter. There has also been some theoretical attempts to resolve this issue (Jandel *et al* 1987a).

The elastic scattering cross section of the various mu-atomic isotopes and the hyperfine transition effects have been studied (Bertin *et al* 1972, 1975, 1978-79, Breunlich *et al* 1989, Cohen 1989).

Another topic of interest that has been generated of late in μcf research is the prediction of resonant states and the study of fusion from these states (Froelich *et al* 1989, 1990, Hu and Bhatia 1990). This is an attractive possibility as sticking is expected to be low for this kind of pre fusion scene. In particular, reactions like

$$\alpha\mu + t \rightarrow (\alpha\mu t)^{**} \rightarrow t\mu + \alpha \qquad (5.2)$$

(where $(\alpha\mu t)^{**}$ refers to a resonance) could be particularly important in reducing sticking via regeneration.

6. *Energy levels and wave function for muonic molecules*

The muon – two nuclei Coulomb bound states project a three body system where two partners are of roughly equal mass and the third is about a tenth as massive as the others. This makes dubious the use of the Born Oppepheimer type of approximation for muonic molecules, although it is found to be so useful for ordinary molecules because of the much smaller mass of the electron. The large mass difference between the lighter lepton, electron and the nuclei justifies the decoupling of the leptonic and nuclear motions and the adiabatic Born Oppenheimer Approximation works rather well for ordinary Hydrogenic molecules. However, this decoupling of leptonic and nuclear motion progressively decreases in validity as we increase the leptonic mass and is not considered suitable for the muon.

Ponomarev's group used expansions in Born Oppenheimer basis states to calculate very accurately the muonic molecular bound states (Bracci and Fiorentini 1982). The calculations predicted some very weakly bound levels that were found to play a pivotal role in resonant molecule formation.

The energy levels were first verified by sophisticated variational calculations in 1984 (Bhatia and Drachman 1984, Frolov and Efros 1984). Since then many other variational calculations have been performed (Kamimura 1988, Puzymin and Vinitsky 1988, Alexander and Monkhorst 1988 and others) and impressive accuracies have been reached. Table 1 shows some of the values for these binding energies (Ponomarev 1990). Important corrections to the Coulomb energies include relativistic and other effects, corrections due to other particles in the molecular complex, spin and nuclear effects (Aissing and Monkhorst 1990, Szalewicz et *al* 1990, Kammimura 1988). Binding energies are required accurately,

Table I(a). Binding energies $|\epsilon_{Jv}|$ in eV, of muonic molecular (Jv) states.

(Jv) Molecule	(00)	(01)	(10)	(11)	(20)	(30)
$pp\mu$	253.152	—	107.266	—	—	—
$pd\mu$	221.549	—	97.498	—	—	—
$pt\mu$	213.840	—	99.127	—	—	—
$dd\mu$	325.074	35.844	226.682	1.97482	86.434	—
$dt\mu$	319.140	34.834	232.472	0.66017	101.416	—
$tt\mu$	362.910	83.771	289.142	45.206	172.652	48.813

The values in the table are takan from Ponomarev 1990.
For $dt\mu(11)$ Aissing and Monkhorst recently report a binding energy of 0.596.6 eV (Aissing and Monkhorst 1990).

particularly for the weakly bound levels, crucial for molecule formation. The vacuum polarisation effects on muonic molecular energies have been investigated and analytic algorithms developed (Petelenz and Smith 1987).

Table I(b). Relativistic and other corrections (meV) to nonrelativistic energies ϵ_{11}^{NR} of $dd\mu$ and $dt\mu$ states ($J=v=1$).

Corrections	Notation	$dd\mu$	$dt\mu$
Nonrelativistic energy, meV	ϵ_{11}^{NR}	−1974.82	−660.17
Vacuum polarization	$\Delta\epsilon_{11}^{VP}$	8.7	16.6
Nucleus electromagnetic structure	$\Delta\epsilon_{11}^{FSZ}$	−1.5	13.3
Relativistic shift	$\Delta\epsilon_{11}^{rel}$	1.4	0.1
Electron screening and μ-molecule finite size	$\Delta\epsilon_{11}^{dim}$	1.0	0.3
Nuclei polarization	$\Delta\epsilon_{11}^{pol}$	0.0	1.9
Corrections to nuclear forces	$\Delta\epsilon_{11}^{nucl}$	$<10^{-4}$	$<10^{-4}$
Energy level total shift	$\Delta\epsilon_{11}^{tot}$	9.6	28.4
Resulting energy	ϵ_{11}	−1965.3	−631.8

These values are taken from Ponomarev 1990.

The culture of high precision Coulomb bound state calculation has produced also very accurate muomolecular, wave function that have been successfully used to compute many of the muon catalysed fusion rates. It is sometimes felt, however, that while these functions are very useful for high precision calculations of the parameters of the electromagnetic sectors, they may not be quite so accurate in describing the fusion potential of the molecule and the post fusion physics (Chatterjee and Gautam 1983, Hale *et al* 1989).

The importance of incorporating nuclear effects into these wave functions was pointed out (Rafelski and Müeller 1985, Danos *et al* 1986, 1987, 1989, Takahashi 1986b) and attempts to estimate the nuclear perturbations have also been made.

7. *Formation of muonic molecules*

Starting with a neutral muonic atom, formation of muonic molecules can occur in two types of reactions with target molecules. These are characterised by the form of the energy release. We remind ourselves that the ground state muonic atom is a spatially tiny system with a correspondingly close overlap of the positive and negative charges. Its resulting motion through the surrounding molecules simulates neutral neutron-like behaviour and it can penetrate easily through the electronic cloud to interact and join with the nuclei to form muonic molecules.

The non resonant auger process is familiar from electron atom physics (Figure 2a)

$$(\mu N_i)+(N_j e_1 N_k e_2)-(\mu N_i N_j)+(e_1 N_k)+e_2 \ (+j \leftrightarrow k) \tag{7.1}$$

N_i, N_j, N_k refer to the three nuclear isotopes of hydrogen. The auger electron carries away the energy released.

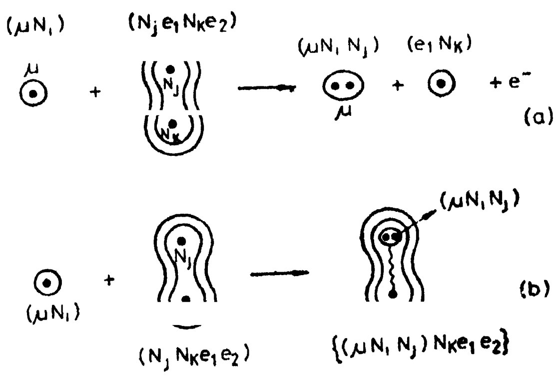

Figure 2(a). Muonic molecule formation by auger mechanism.
2(b). Resonant formation of muonic molecules.

The resonant mechanism makes possible the high formation rates that permit high fusion rates. In this case the energy release is used to excite the host molecule which does not dissociate (Figure 2b)

$$(\mu N_i)+(N_j N_k e_1 e_2)-[(\mu N_i N_j)N_k e_1 e_2]^*+(j \leftrightarrow k) \tag{7.2}$$

The muonic atom forms a muo-molecule with one of the nuclei of the target molecule and this muo-molecule remains within the target molecule which is excited to one of its higher ro-vibrational states. The other nucleus remains a spectator. The muo-molecule acts as one of the nuclei of the final molecular complex. This mechanism was proposed by Vesman (1967). The condition for resonance is

$$\epsilon = \epsilon_r = (\Delta E - E_b) \tag{7.3}$$

where ϵ is the energy of the incident μ atom, ΔE is the difference in energy between the level being excited and the initial level and E_b is the binding energy of the molecule.

This is possible only when the muo-molecule has a binding energy lower than the dissociation energy of the host molecule.

The molecule formation rate can be written for the $dt\mu$ system as

$$\lambda_{dt\mu} = N_0 \int_0^\alpha \sum_{i,f} W_{ki} \mid M_{fi} \mid^2 2\pi\delta(\epsilon - \epsilon_{r_i})\, f(\epsilon, T) d\epsilon \tag{7.4}$$

W_{ki} represents the temperature dependent occupation of rotational states of the initial D_2 target molecule. K_i, ϵ_{r_i} are the resonance energy and $f(\epsilon, T)$ is the distribution of initial kinetic energy ϵ in the center-of-mass system. The Maxwell distribution of the $(t\mu)$ atom is thermalised. The effects of epithermal energies of the incident $(t\mu)$ atom on the $(dt\mu)$ muonic molecule formation is important and has been studied in detail (Leon 1984, Cohen and Leon 1985). The effects of thermal spikes has also been looked at (Jandel 1988).

While the resonance formation was observed initially for the $dd\mu$ system, it does not enhance the molecule formation as greatly as for the $dt\mu$ case because the $dd\mu(1, 1)$ weakly bound state amenable to resonance mechanism is more tightly bound than the corresponding $(1, 1)dt\mu$ state (see Table 1).

Experimentally it appears that the $dt\mu$ molecule formation rate does not go to zero at low temperature and its dependence on target density is nonlinear. Explanations based on below threshold resonances invoking broadening of the resonances and three body interactions have been proposed to explain this (Cohen 1989, Faifmann et *al* 1988, Cohen and Leon 1989).

The principle of resonant molecule formation provokes the possibility of enhancing the rate, if a suitable target is found where the molecular level spacing is larger (Chatterjee 1984). A perturbation calculation (Chatterjee *et al* 1986) indicated this could be artificially induced using a laser field. Detail calculations of μcf in a laser field have since been done (Takahashi 1989, Eleizer et *al* 1989).

8. *Deexcitation and stabilisation of muonic molecules*

Deexcitation and the subsequent stabilisation of the resonantly formed muonic molecule is an essential prerequisite to fusion. Thus 'back' decay through the entrance channel should be avoided. For this, a quick deexcitation from the $J = 1$

state the resonant mechanism populates, to a lower state, more conductive to fusion of its nuclei is desirable (Fusion rates from $J=0$ and $J=1$ states are $\sim 10^{11}$ sec^{-1} and $\sim 10^{8}$ sec^{-1} respectively for $dt\mu$).

The dominant deexcitation process is by Auger effect where an orbital electron carries away the deexcitation energy in an analogue to the internal conversion process.

We computed (Bhatia *et al* 1988) the rates for the Auger deexcitation between the various states for the $dt\mu$ system. Variational wavefunctions obtained earlier (Bhatia and Drachman 1984) were used for this, with the simplification that the muon is in an S state while the angular momentum is carried by the nuclei as these are the most important terms.

$$\Psi = Y_J^m(\Omega r_{td}) \exp\left\{-(\alpha r_{td} + \gamma r_{t\mu}) \sum C_{lmn} r_{td}^l r_{t\mu}^m r_{d\mu}^n\right\} \tag{8.1}$$

where subscripts refer to the particle connected by the respective r The various possible transitions are shown in Figure 3.

In the above work the muonic molecule has been treated as the acting nucleus of a hydrogenic system. The spectator nucleus and second electron

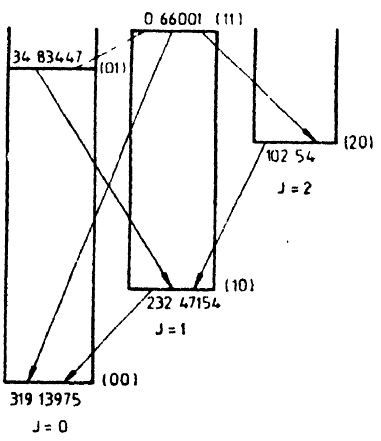

Figure 3. The deexcitation channels for the $(dt\mu)^*$ molecule (Bhatia *et al* 1988).

of the host molecule are not taken into account. Since each multipole term of the transition operator separates quite accurately into electronic and muonic systems these variational results can be used in the molecular background without recalculation. The leading dipole transition rate takes the form

$$\lambda = 5.519 \times 10^{12} \beta F_{coul}(q) I^2/(2J_i+1) \text{ sec}^{-1} \tag{8.2}$$

where

$$F_{coul}(q) = \frac{2\pi}{(1+q^2)(1-e^{-2\pi/q})} \exp\left[-(4/q)\tan^{-1} q\right] \tag{8.3}$$

J_i is angular momentum of initial state, β depends on the transitions, I is the dipole transition matrix element (Bhatia *et al* 1988), and q depends on the energy difference between the initial and final state. Bogdonava and co-workers have calculated this from the molecular state (Eogdonava *et al* 1982).

The total deexcitation rate of the (1, 1) state is 6.46×10^{11} sec^{-1} is in competition with back decay, and population of the excited $J=0$ state is heavily favoured. The Auger deexcitation has also been computed recently (Scrinzy and Szalewicz 1989, Armour and Lewis 1990).

The problem of back decay, as an impediment to fusion, was pointed out by Lane in the context of *d-d* fusion (Lane 1985, Leon 1985). If the molecule formation reverses and returns the $(t\mu)$ to its atomic state, then fusion is no longer possible.

9. *Nuclear fusion in the muonic molecule*

Muon catalysed cold fusion provides a unique example of a sub-barrier fusion reaction put on threshold by its electromagnetic coupling to a spectator muon. The large mass of their leptonic partner in the muonic molecular state imposes a spatial confinement on the nuclei, restricting their seperation to distances $\sim 10^{-11}$ cm. At this close proximity the probability of sub-barrier fusion of the nuclei becomes very high and fusion is practically instantaneous once the strongly bound muonic molecules are formed.

The traditional approach of estimating the fusion rate combines the integral of the three particle Coulomb wave function at nuclear contact with the nuclear reaction cross section at very low relative velocities. Thus the literature displays the formula for the fusion rate (Bhatia and Drachman 1989)

$$\Gamma_f = \lim_{V \to 0} \frac{\sigma V}{C_0^2} \int dr \left| \psi_{N_1 N_2 \mu}(r, r_{N_1 N_2} = 0) \right.$$

with V being the relative nuclear velocity. N_1, N_2 refer to the two nuclei and σ is the relevant reaction cross section. C_0^2 is the Gamow factor given by

$$2\pi\xi/[e^{2\pi\xi} - 1], \; \xi = \frac{\alpha c}{V}$$

for the relative S state.

Table 2 shows the fusion rates for the different isotopic combinations and is taken from a recent paper (Alexander *et al* 1990). Some of the other values are also indicated. It is seen that fusion rates are much smaller from the $J=1$ states due to the centrifugal barrier, and that *t-d* fusion is the most favoured. For the $(dt\mu)$ molecule, as discussed in Section 8, Auger deexcitation rapidly populates the $J=0$ states from which the fusion rate is very high.

Calculations of the fusion rate incorporating nuclear effects have been reported (Szalewicz 1990). It has also been commented (Hu 1990) that hermiticity conditions of these should be checked and so this area still contains room for improvement. A proper microscopic theory with correct inclusion of

Table 2. Fusion rates (in sec^{-1}) of the mesomolecular ions xy^{μ}. The rate constant A_s has units of cm^{-3} sec^{-1} and A_p has unit of cm^{-5} sec^{-1}. $|F(0)|^2$ has units of cm^5 for the homonuclear $J=1$ states and cm^3 for all other states. All digits shown for this quantity have converged. $x(y)$ represents $x \times 10y$.

	A_s	$\|F(0)\|^2$		Reaction
$tt\mu$ (00)	7.5 (−7)	1.4 (25)	9.5 (8)	$t + t$ — $n + n + {}^4$He
$tt\mu$ (01)	7.5 (−7)	1.28 (25)	1.0 (9)	$t + t$ — $n + n + {}^4$He
$td\mu$ (00)	1.3 (−14)	5.296 (25)	6.9 (11)	$t + d$ — $n + {}^4$He
$td\mu$ (01)	1.3 (−14)	4.43 (25)	5.8 (11)	$t + d$ — $n + {}^4$He
$td\mu$ (10)	1.3 (14)	8.5 (21)	1.1 (8)	$t + d$ $n + {}^4$He
$td\mu$ (11)	1.3 (−14)	3.4 (21)	4.4 (7)	$t + d$ — $n + {}^4$He
$dd\mu$ (00)	7.5 (−17)	1.45 (26)	1.1 (10)	$d + d$ — $n + {}^3$He/$p+t$
$dd\mu$ (01)	7.5 (−17)	9.97 (25)	7.5 (9)	$d + d$ — $n + {}^3$He/$p+t$
$tp\mu$ (00)	4.8 (−21)	5.0763 (26)	2.4 (6)	$t + p$ — $\gamma + {}^4$He
$tp\mu$ (10)	4.8 (−21)	4.8 (23)	2.3 (3)	$t + p$ — $\gamma + {}^4$He
$dp\mu$ (00)	5.2 (−22)	8.720 (26)	4.5 (5)	$d + p$ — $\gamma + {}^3$He
$dp\mu$ (10)	5.2 (−22)	4.8 (23)	2.5 (2)	$d + p$ — $\gamma + {}^3$He
$pp\mu$ (00)	4.7 (−40)	2.349 (27)	1.1 (−12)	$p + p$ — $e^+ + \nu^- + d$
	A_p	$\|F(0)\|^2$	λ	Reaction
$tt\mu$ (10)	2.49 (−40)	1.6 (48)	4 0 (8)	$t + t$ — $n + n + {}^4$He
$tt\mu$ (11)	2.49 (−40)	1.4 (48)	3.5 (8)	$t + t$ — $n + n + {}^4$He
$dd\mu$ (10)	2.85 (−40)	7.69 (48)	2.1 (9)	$d + d$ — $n + {}^3$He/$p+t$
$dd\mu$ (11)	2.85 (−40)	2.4 (48)	6.8 (8)	$d + d$ — $n + {}^3$He/$p+t$
$pp\mu$ (10)		2.66 (49)		$p + p$ — $e^+ + \nu^- + d$

Taken from Alexander *et al* (1990).

the kinematic final state constraints would be useful. The details of the conservation delta function dictates have been studied recently (Chatterjee 1989a, 1990a, c).

The *d*-*d* fusion presents an interesting combination where the two exit channels are asymmetric with regard to the available kinetic energy and the number of charged particles. The only experimental measure of the branching ratio $R = \Gamma_{n-He}/\Gamma_{t-p}$ from $(dd\mu)$ fusion was obtained in a sophisticated ionisation chamber experiment (Balin et *al* 1984). This experiment obtained a value of $R = 1.39 \pm 0.04$ which was considered puzzling because of the violation of isospin symmetry it represents. Attempts to explain this large value of R invoke *p*-wave interaction between the fusion nuclei, assuming *d*-*d* nuclei to be in a relative *p* state in the $(dd\mu)$ molecule. A recent theory using R matrix analysis reports a value of 1.43 for this ratio (Hale 1990). Other calculations also appear to vindicate the experimental measure of this quantity (Breunlich et *al* 1989). Phase space criteria on the other hand favour the *t*-*p* channel due to the extra available energy if one imposes isospin symmetry at the reaction vertex (Chatterjee 1990b). Low energy amuonic nuclear data indicate a favouring of the *t*-*p* channel at very low energies, the trend reversing to favour the n-^{3}He channel at higher energies (Theus et *al* 1966). The *d*-*d* fusion has also been studied in a direct reaction frame-work (Obberheimer et *al* 1990).

The *t*-*t* fusion has been studied experimentally by the PSI group (Breunlich et *al* 1987b).

10. Post fusion final states

In most cases the post fusion era finds the muon released and free to repeat the catalysis cycle. However, in some cases the muon emerges 'stuck' in a Coulomb bound state with one of the charged fusion products. For fusion from the $(dt\mu)$ muomolecule for example, the two exit channels corresponding to stuck and non-stuck post fusion scenes are

$$(dt\mu)\begin{array}{l}\nearrow \alpha+n+\mu \text{ (non stuck)}\\ \searrow (\alpha\mu)+n \text{ (stuck)}\end{array} \tag{10.1}$$

We shall discuss the details of sticking in the following section.

The case when the muon is left free after *d*-*d* or *d*-*t* fusion belongs to the class of post reaction kinematics where there are three exit channel particles. This is because although the muon is spectator to the fusion event its role is linked to the exit channel because of its Coulomb link to the reactants in the pre-fusion zone. General spectator behaviour indicates the muon should be left behind with approximately the momentum it had in its bound state while the nuclear reactants rapidly leave the fusion scene. On the other hand treatment of the spectating muon as a bonafide final state particle that participates in the exit channel kinematics would be more rigorous. The fusion event unfolds in the electromagnetic field of the spectator muon and its role is inextricably mapped into the final state observables as well as the pre-fusion sector (Chatterjee 1990a, c). The delta function constraints on the non-stuck exit channels have been studied recently for the *d*-*t* and *d*-*d* entrance channels (Chatterjee 1989a, 1990). The post fusion muon has also been studied by other groups (Müller et *al* 1989, Jandel 1989d, Shin and Rafelski 1990).

11. Sticking

Sticking has already been introduced as corresponding to the cases where the muon sticks to the doubly charged fusion product (Sec. 10). It is then lost to the catalytic chain unless it can be reactivated or stripped. Currently it forms one of the major bottlenecks to utilising μcf.

In the case of d-t fusion the muon is found 'stuck' to the final alpha is less than 1% of all fusion events while for d-d fusion the percentage sticking to ^{3}He is ~12%.

Experimentally the earlier measurements of sticking were obtained from the fusion neutron count and the Los Alamos experiments with the d-t system first indicated sticking could be much lower than the expectations of earlier theories (Jones *et al* 1983). This led to a dramatic increase of interest in muon catalysed fusion as it implies a significant gain in the application potential. The low value of sticking at high densities has been reconfirmed by the PSI group (Breunlich *et al* 1987). However, the strong inverse dependence of density reported by the Los Alamos experiment appears to be controversial.

Recently, direct measurements of sticking (Paciotti *et al* 1989, Davies 1989) have been performed and also X-ray measurements on the $(\alpha\mu)$ have been carried out (Bossy *et al* 1987, Nagamine *et al* 1986).

Theoretically too, sticking has been much analysed. 'Intrinsic' sticking (ω_s^0) refers to the actual sticking that occurs in direct overlap with the fusion event. Subsequently, there is often rapid 'stripping' of the intrinsically stuck muon (Cohen 1987, Stodden *et al* 1990). 'Stripping' occurs by transfer to d or t nuclei until the $(\alpha\mu)$ is slowed down. What is usually observed in the experiments is the 'effective' sticking (ω_s) remanant after the stripping process.

Theoretically, intrinsic sticking is generally computed in the sudden approximation by taking the overlap of the muon's initial wave function with its final wave function in a state bound to the escaping alpha. In the absence of the muon the two particle nuclear exit channel leaves the alpha with rather high energy in d-t fusion.

If the muon is to tag along with the alpha in a 'stuck' state, it should overlap it in velocity space. The initial muon velocity distribution in its bound molecular state imposes a strong supression on high velocity final states, if simple overlap matrix elements are used. Therefore, the sticking probability is low in d-t muon catalysed fusion.

However, it is not low enough, and given the high $(dt\mu)$ molecule formation rates by the resonance mechanism, sticking provides one of the major hurdles to utilising this kind of cold fusion.

In the literature, intrinsic sticking is defined in the sudden approximation framework as

$$\omega_{nl}^{0} = \left| \int dr\, e^{-ik.r} \phi_{n,l}(r)\, \psi_{dt\mu}(r, r_{td}=0) \right|^2 \qquad (11.1)$$

ϕ_{nl} is the hydrogenic wave function of $\alpha\mu$ in the (n, l) state, and k is the momentum vector of a muon moving with the velocity of the $(\alpha\mu)$ atom. $\psi_{td\mu}$ is assumed to be normalised to unity at $r_{td}=0$.

While ω^0_{nl} gives the sticking into the (n, l) stuck state, the total intrinsic sticking is obtained as $\omega^0_s = \sum_{n,l} \omega^0_{nl}$.

Earlier estimates of sticking using Born Oppenheimer wave functions predicted ~1% sticking in $dt\mu$ fusion (Bracii and Fiorentini 1981, Jackson 1957). Subsequently, use of improved wave functions yielded lower values of the sticking fraction (Hu 1986, Bogdanova et *al* 1986, Haywood et *al* 1988). However, discrepancy between theory and experiment persists (Cohen 1989). For the $dt\mu$ system intrinsic sticking is reported as $\omega^0_s \sim 0.88\%$ using variational wave functions.

The need for including nuclear effects and other corrections and a better formulation of the sticking calculations has bsen pointed out (Hale et *al* 1989, Chatterjee 1989, Danos et *al* 1987, Hale et *al* 1988). It has also been reported that use of proper delta function constraints and final state kinematics can reduce sticking (Chatterjee 1989, 1990). Calculations incorporating nuclear effects have been reported (Szalewicz et *al* 1990).

Theoretical estimates of effective sticking (Cohen 1987) approach the experimental high density value but remain higher. Recent reports indicates the match between theory and experiment to be closer (Preliminary reports of PSI and RAL experiments, et *al* 1990).

Effective sticking ω_s is obtained from intrinsic sticking ω^0_s as

$$\omega_s = \omega^0_s(1 - R)$$

where R is the reactivation factor.

The reactivation factor R was initially computed with a simplified kinetic description in 1981 (Bracci and Fiorentini 1981). Subsequently, an exhaustive study of this was carried out with complete treatment of the different $(\alpha\mu)$ kinetics channels (Cohen 1987). Other calculations (Stodden et *al* 1990) have also been reported.

Feasability of using laser beams or a plasma environment to reduce sticking have been probed and are discussed in Part II.

PART II : Utilisation Prospects

1. Application possibilities

Muon catalysed fusion synthesises a complex interplay of different interactions. While portraying fascinating fundamental physics issues, its importance is further enhanced due to its rich application potential. In the backdrop of the green house effect and the ozone hole, and humanity's inability to survive without energy, any new energy source with a clean exhaust system acquires technical and political advantage. In this sense muon catalysed fusion rather neatly fills the bill by offering a relatively clean source of nuclear energy. This it shares with other forms of nuclear energy.

In fact most μcf application scenarios at present envisage a combined fusion-fission hybrid system, although pure cold fusion devices are also thought of. Accepting that for the distant future atleast, pure fusion energy should be the ultimate goal due to both fuel and exhaust advantages, one reaches the cross roads of which path is the easiest to achieve self-sufficient fusion. High temperature plasma fusion and laser aided fusion have become the traditional route towards this goal. Important advances, both theoretical and experimental have been made in the field, and impressive technical progress has been achieved at both the international and national level.

However, despite the considerable work done, break-even still eludes plasma fusion – and we explore in parallel the prospects of low temperature sub-barrier fusion. It is felt that both routes are away from 'break-even' by roughly a factor of ten. We repeat that the recent reports of amuonic cold fusion do not form the subject matter of this review.

Commercial utilisation of sub-barrier nuclear fusion catalysed by negative muons depends on the favourable balance of the different competiting parameters.

The primary hurdle is Nature's frugality in providing natural muons. Cosmic ray muons that shower the earth are woefully inadequate with respect to flux requirements for useful catalysis of fusion events. This has been discussed in some recent papers (Harms 1986, Chatterjee 1989).

We must therefore make the muons we need for muon catalysed fusion. This makes the muon production cost a crucial parameter for μcf utilisation.

The muon cycling rate λ_c or the number of fusions a single muon can catalyse in its brief lifetime of 2.2×10^{-6} sec depends on the different stages of the fusion cycle.

The resonant mechanism provides a high rate of $dt\mu$ molecule formation ($\sim 10^9$ sec^{-1}) at room temperatures as discussed in Part I. The number of fusions accessible per muon is therefore controlled chiefly by two factors – the fractional loss W and the muon decay rate. In fact even if W could by some means be drastically reduced, we still have to contend with the sobering fact of the muon's finite lifetime. Interestingly enough, both these impose roughly the same limit of about 300 fusions per muon (Cohen 1989). However, it has also been pointed out (Jones 1987), that extrapolation of current Lampf results to high density mixtures can give $N \sim 1500$ when $W \rightarrow 0$.

For efficient utilisation, the cycling rate should be optimised and the fractional loss per cycle minimised. All these issues have been addressed. It is generally felt that a hybrid system would already be a viable proposition. Regarding a pure fusion device, opinions differ on the exact number of fusions required for commercial break even with a pure fusion device. A steady presence of $\sim 10^6$ muons corresponding to a flux of $10^6/2.2 \times 10^{-6}/\text{sec} = 70$ nA muons is expected to be required to generate a continuous thermal power of about 1.5 MW (Rafelskii 1989).

2. *The experimental set-up*

We take a brief look at the experimental arrangements of the μcf experiments of the eighties and their projection into the nineties.

In principle the experiments are of four main kinds. The fusion neutron detection method counts the fusion neutrons. The μcf parameters like molecule formation rate and sticking are derived quantities. The LNPI ionisation chamber is able to measure all post-fusion charged particles efficiently. The importance of accurate evaluation of sticking has inspired the new generation 'direct sticking' experiments that measure the alpha and $(\alpha\mu)$ ions. Finally the X-ray measurements on the $(\mu\alpha)$ system yield valuable information.

Figure 4 shows a schematic diagram of the 1983 Los Alamos d-t experiment (Caffrey *et al* 1986) that demonstrated many fusions per muon. The muon beam enters the fusion chamber and fusion neutrons are detected by the neutron detectors. Muon decay electrons signal the stopped muons. The cycling rate λ_c or the number of fusions per muon is obtained as a function of target density, temperature and tritium fraction. Clean extraction of the different μcf parameters corresponding to rates of the different competing channels depicted in Figure 1, (Part I Section 3) is naturally extremely complicated. As mentioned in Part I, under certain experimental conditions the cycling rate equation simplifies and the molecule formation rate, d-t transfer rates and sticking coefficients can be obtained. Recent Lampf experiments indicated over 150 fusions per muon (Jones 1986).

μcf studies at the PSI (or SIN, as it was then called), developed out of an impressive culture of dedicated weak interaction experiments at the muon facility (Breunlich 1981). The importance of hyperfine effects in $(dd\mu)$ μcf studies was established during the 1980 experiments that looked at the temperature dependence of the molecule formation rate (Breunlich *et al* 1984). The measurements on the $dt\mu$ system by the PSI collaboration confirmed the occurrence of over 100 fusions per muon (Breunlich *et al* 1987a). The details of the experiments have been reported in the referred papers. Measurements on the t-t fusion were also carried out (Breunlich *et al* 1987b).

The LNPI group at Gatchina made the only measurement of the (n-^{3}He) to (t-p) exit channel branching ratio in a sophisticated ionisation chamber experiment. 100% efficiency was claimed for detection of charged particles due to (4π) detection facility (Balin *et al* 1984). Other μcf parameters were also measured.

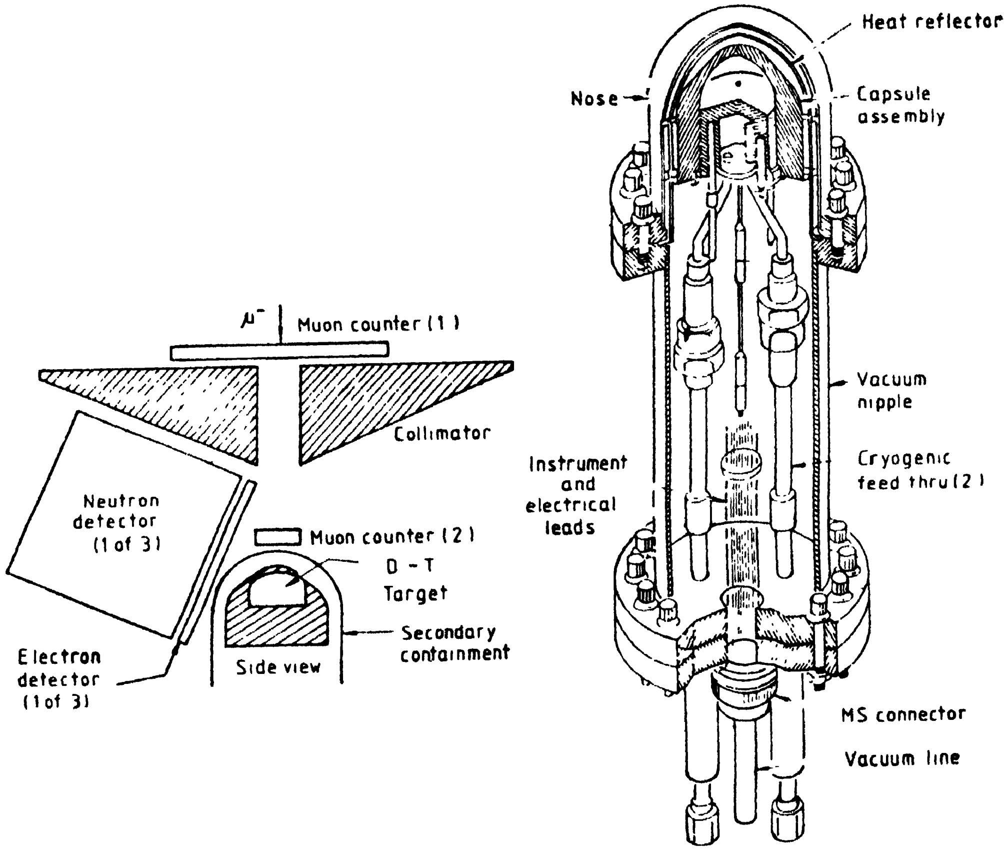

Figure 4. The experimental set up for the Los Alamos experiments. (Taken from Caffrey *et al* 1986).

The need to obtain an accurate measure of the sticking fraction in a 'clean' manner without contamination from other parameters inspired the development of the 'direct' sticking experiments for d-t system. These count directly the alpha and ($\alpha\mu$) ions in coincidence with fusion neutrons. This gives 'direct' measure of the branching ratio for sticking, without having resort to its derivation from the cycle rate.

Direct sticking experiments have been carried out at Rutherford Lab., UK (Davies *et al* 1989, 1990) and at Lampf. The pulsed beam at RAL is specially suited for the experiment. Recent PSI experiments also report direct sticking measurements.

Measurement of X-rays emitted during μcf processes add richness to existing experimental data (Bossy *et al* 1987). The X-ray measurements at the KEK Pulsed muon facility have provided information on the post-fusion ($\mu\alpha$) system (Nagamine 1986). Other experiments are in progress.

The earlier μcf experiments were Bubble Chamber and counter experiments in USA and at Dubna, USSR (Bracci and Fiorentini 1982).

3. *Muon production*

Decay of pions produced in high energy inelastic collisions of nuclei provides so far the best source of muons. Muon production costs are therefore intimately related to the cost of producing the parent pion. Existing muon factories produce muon beams purely for research purposes so that they have not been optimised for cost efficiency for fusion turn around. Since negative muons are required for μcf, one seeks a favouring of the negative charge state amongst the produced pions.

The importance of increasing the efficiency for pion and hence muon production was realised during the infancy of μcf research. The advantage of triton-triton collisions for negative pion production was established by Petrov and Shabelski (Petrov and Shabelski 1979). They also estimated the energy cost per muon. Since then different aspects for this problem have been studied in detail. The most efficient primary projectile energy from point of view of maximising pion production, yet minimising accelerator costs, have been investigated by different techniques (Moir and Chapline 1986, Takahashi 1986a, Bertin *et al* 1987, Chatterjee 1987, 1989c, Jandel *et al* 1988, Jandel 1989, Chatterjee *et al* 1989). Jandel *et al* also probed the feasibility of combining the pion producing target with the fusion hosting medium (Jandel *et al* 1988). Current estimates place the cost of muon production around 5 Gev/μ ranging from (2-5) Gev/muon. Given a fusion energy release of 17.6 MeV per d-t fusion for instance, for 'energy break even' conditions, one requires about 300 fusion per muons for a muon production cost of 5 Gev/muon. It may be noted that scientific break-even defined through (muon mass/energy gain) per muon is already crossed at about 5 fusions per muon, and for the d-t system, experiments bear clean evidence of well over 100 fusions.

4. *Muon losses*

The chief source of muon loss as we have already seen is sticking and this provides one of the major hurdles to achieving unlimited fusion. The possibilities of reactivating the stuck muon has also been discussed (Part I, Section 11).

Several methods for reducing sticking by adjusting external parameters have been suggested. These include use of laser fields (Takahashi 1989, Eleizer *et al*

1989) or electric fields. Advantages of low temperature plasma environment has also been studied.

Scavenging of post-fusion muons by helium ions forms another major source of muon loss (Leon *et al* 1988, Bertin *et al* 1989). In addition to this muons are lost to the nuclei of the material housing the fusion medium and the total muon loss is comprised of the different partial losses.

5. *Reactor concepts*

The earliest reactor concept for using μcf energy was proposed by Petrov (Petrov 1980). This is shown in Figure 5. In a thick Uranium (238 U) blanket, one 14 MeV neutron can produce one fusion and four extra neutrons. These can provide about 2.4 *Pu* nuclei for further burning and one tritum nucleus to replace the burned one. Since each *Pu* nucleus in a reactor can give 1.6 fissions, one can recover the energy of some 5 fission reactions, i.e. about 1 GeV energy per fusion catalysed by the muon. Subsequently the feasibility prospects have been studied further (Petrov 1988, Eliezer *et al* 1987).

A comparative study with other systems has also been done in the series of papers (Petrov 1980, 1987). Thus as a plutonium producing device for satellite thermal reactors, it differs advantageously from fission fast-breeders by a high

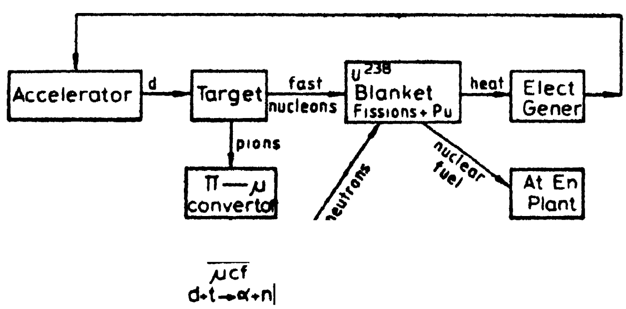

Figure 5. The hybrid fission fusion reactor (Petrov 1980).

rate of plutonium production per unit power and by the lack of necessity to deal with highly enriched fuel. The latter is extremely important from the viewpoint of nonproliferation of fission materials for nuclear weapons. The other essential advantages is that the HMCR (Hybrid mesocatalytic reactor) is a deeply subcritical system so that the possibility of its nuclear explosion is completely eliminated, though, of course, the satellite reactors, fed by the HMCR, remain critical systems. However, taking into account the progress in the field of thermonuclear safety, one might hope that the symbiotic systems "HMCR+TRs" will take their place in the nuclear energetics of the XXIst century (Petrov and Sakhnovsky 1988).

Breeding of tritium from lithium can be used as accessory energy gain in a pure μcf reactor (Jones 1987). M Jandel *et al* (Jandel *et al* 1988) have proposed an 'active target' system where the pion producing projectile beam is dumped into the fusion vessel itself where the *D-T* mixture plays the dual role of being the target for pion and subsequently muon production as well as supplying the fusion reactants. This scheme visualises a pure fusion device and tritium breeding is included in the gain.

Another scheme for a pure fusion reactor without resorting to breeding of fissile matter has been conceived by Tajima *et al* (Tajima *et al* 1989). This involves immersing *DT* ice ribbons in a magnetic field. The field configuration is designed to confine the pions created by an injected *d* or *t* beam. The overall bundle of ribbons is inertially confined and is expected to aid stripping.

Engineering challenges and technical issues have been studied (Jones 1985). Detailed studies of the energy gain and cycle symbioses have been carried out (Harms 1983, Harms *et al* 1990, Miley 1984).

6. μcf tomorrow

We have journeyed through the fascinating physics of muon catalysed fusion with its multifaceted, interdisciplinary characteristics. Having survived the 'Zitterbewegengs' in its career through the sixties and seventies, and having crossed a more stable and positive era in the eighties, *μcf* is now poised on the threshold of tomorrow. We have ahead the promise of a clean efficient low temperature fusion energy source in parallel with the exciting physics of an intricate admixture of nuclear and electromagnetic interactions.

We have progressed far on the road to understanding the different parameters of the *μcf* cycle. Yet we still have a long way to go achieve complete delinking of the *μcf* parameters and complete understanding of the details of the cycle.

The sensitivity of the parameters to different external effects should be studied from both theoretical and experimental angles. In particular, effects of laser or electric fields and of changing the *μcf* environment to low temperature plasmas or solid states would provide interesting study.

The complexities of the initial electromagnetic muon capture and the slowing down in different environments, the rates for μ atom and molecule formation, sticking and stripping generate research interest for their fundamental physics content. Specifically, the unfolding of the nuclear fusion process in the field of the confining muon and its crucial role in determining the final muon fate provoke deeper incisive study.

On the application side, our goals for tomorrow should have a three pronged approach. Development of cost effective accelerator technology should provide cheaper muon beams. This development should incorporate latest advances in superconducting magnets to further curtail muon production costs (Chatterjee 1987).

Reactor technology for pure fusion devices should be explored with the specific design constraints of μcf in mind. Practical difficulties are expected to impose additional time lags on commercial utilisation even after theoretical and experimental break-even are realised. While it is generally believed that 1000 fusions per muon is the requisite number for commercial break even, the feasibility of smaller numbers has been discussed. Energy break even can be achieved with a number as small as 250 fusions per muon (Jones 1987) and this number may be accessible in future experiments.

Finally, the efforts to reduce sticking and sample different external aids must continue. Accepting the safe goal of 1000 fusions per muon as the needful, we are then a factor of ten off. As remarked earlier this year (Daniel 1990), there is no law of nature against overcoming this factor of ten and new ideas and innovations may well succeed in crossing it. As break even also eludes the other protagonists of controlled fusion by a similar factor of ten (Daniel 1990), we will await tomorrow eagerly and expectantly to see how μcf fares in the race to provide useful sustainable fusion power for the future.

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