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Citation: AIP Conference Proceedings **181**, 2 (1988); doi: 10.1063/1.37915
View online: http://dx.doi.org/10.1063/1.37915
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/181?ver=pdfcov
Published by the AIP Publishing

SURVEY OF EXPERIMENTAL RESULTS IN MUON-CATALYZED FUSION

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INTRODUCTION

Muon-catalyzed fusion research is motivated both by a curiosity about nature and by the possibility of applications. After all, exoergic nuclear fusion is readily induced by negative muons. And muon-catalyzed fusion is indeed curious: we have uncovered many surprises in a rich tapestry of exotic atomic and molecular processes, unexpected resonances, and extremely rapid nuclear interactions. It is remarkable that a fundamentally nuclear process can be affected by changing the temperature and composition of the environment. This phenomenon demonstrates the subtle interplay of atomic and nuclear physics inherent in muon-catalyzed fusion (μcf).

Theoretical and experimental efforts have also dovetailed to expand our understanding of muon catalysis. The theoretical breakthroughs ten years ago achieved by Leonid Ponomarev and his colleagues motivated experiments involving μcf in mixtures of deuterium and tritium. Observed temperature, density and d/t ratio effects in turn led to refinements in the theory. We can say that much progress has been made, but that many areas remained unresolved, some even virtually unexplored.

Overall, we can look back over the past decade of research and conclude that muon-catalyzed fusion yields have significantly exceeded expectations, leading to renewed speculation regarding applications. To guide our discussion of recent progress in μcf research, let us consider a straightforward yet profound equation:

$$1/Y = \lambda_o/\lambda_c + W. \quad (1)$$

where

Y = yield, the number of fusions per muon (average);

λ_o = muon-decay rate (0.455 per microsecond);

λ_c = muon-catalysis cycling rate (1/time between fusion neutrons); and

W = the probability of muon loss per catalysis cycle, for any cause.

It is informative to interpret this governing equation as a sum of probabilities:

1/Yield =	Probability of muon decay during any stage of the catalysis cycle	+ Probability of muon-scavenging due to dead-end processes	(1b)

Clearly, to increase to fusion yield one would try to increase the catalysis cycling rate λ_c, and minimize muon losses W. We will here review what we have learned about these important parameters, then examine the current fusion yields vis-a-vis energy applications for μcf.

THE MUON CATALYSIS CYCLING RATE

Figure 1 displays a subset of data obtained at the Los Alamos Meson Physics Facility since 1982 regarding the observed (unnormalized) muon catalysis cycling rate. (See Ref. [1].) We see that λ_c depends on the density of the deuterium-tritium mixture as well as on its temperature and composition.

Why is this so? Coordinated theoretical and experimental studies have led to a picture of the μcf cycle which is portrayed in somewhat simplified form in Figure 2. Important reaction rates and muon-loss probabilities are labeled on this diagram. Not that C_p, C_d, C_t, and C_{He} represent the atomic fractions of the three isotopes of hydrogen (p,d,t) and helium present in the reaction chamber. The cycling rate can be broken down into component terms according to the prescription:

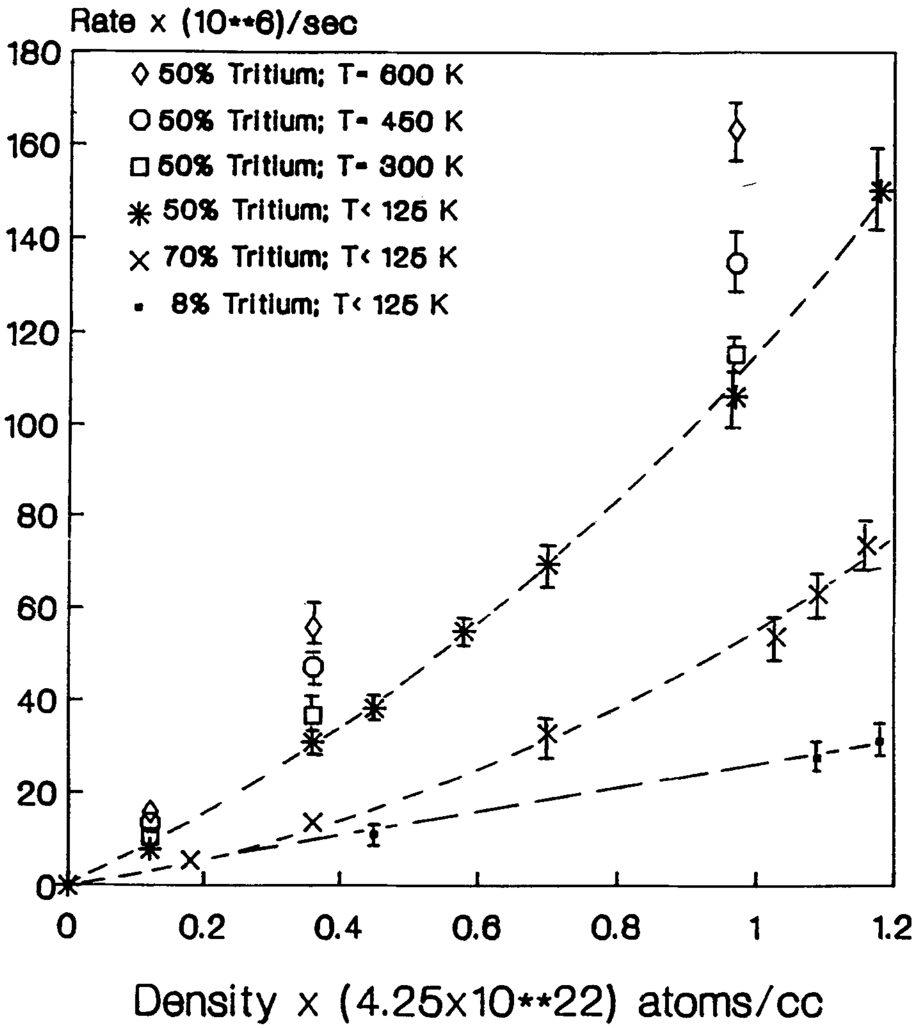
$$\lambda_c^{-1} \approx \left[\frac{q_{1s}C_d}{\lambda_{dt}C_t} + \frac{0.75}{\lambda_{10}C_t} + \frac{1}{\lambda_{dt\mu}C_d}\right]\phi^{-1}. \tag{2}$$

for temperature $\lesssim 500K$, and where ϕ = the density of the target mixture.

The parameter q_{1s} merits further discussion. It represents the probability that the dμ atom will reach the ground state before the muon is transfered to a triton to form a tμ atom, an energetically favorable reaction. The d$\mu \rightarrow$ tμ transfer reaction is faster for a smaller q_{1s}. But experiments [1,2,3] show that q_{1s} is larger than predicted [4] and decreases more slowly with increasing tritium fraction and density than expected. This transfer reaction is a relatively slow one (requiring typically a few nanoseconds), so it is relevant to understand why q_{1s} is as large as it is seen to be, and how it could be

Figure 1.

OBSERVED MUON CATALYSIS CYCLING RATE vs. D-T DENSITY



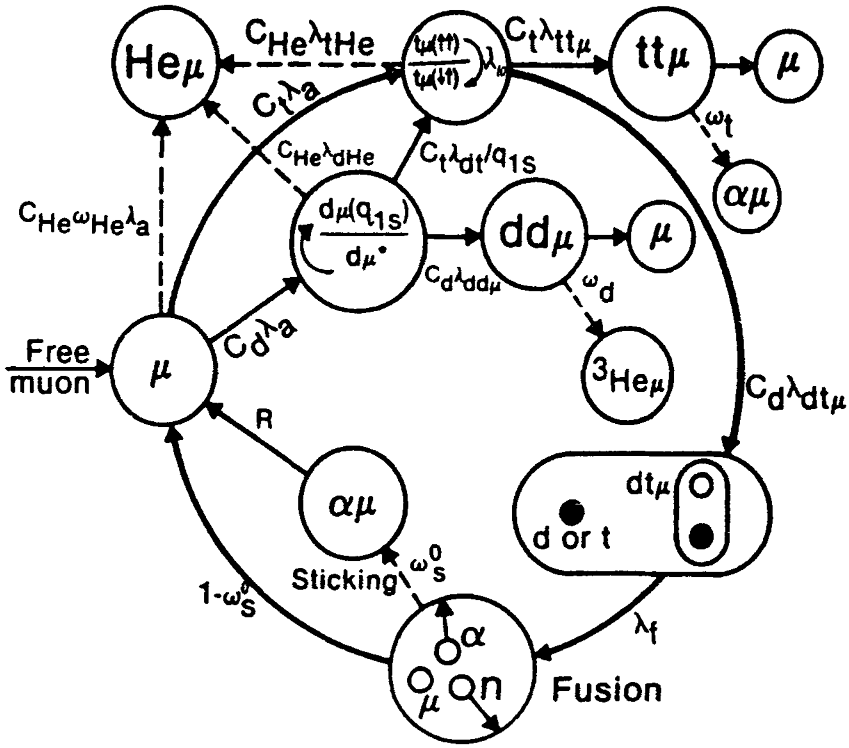


Figure 2. Scheme of the muon-catalyzed fusion cycle, showing reactions which occur when negative muons stop in a mixture of the hydrogen isotopes (p, d, and t) and helium (He) with respective fractions C_p, C_d, C_t, and C_{He}. Reaction rates are labeled with λ, and muon loss probabilities are labeled with ω.

reduced. A method to measure q_{1s} involving competition between the transfer reaction and helium scavenging (see Figure 2) has been described by Mel Leon [5]. Understanding the density, temperature and d/t ratio dependences of q_{1s} is a near-term goal of experiments.

Like q_{1s}, the hyperfine-quenching rate λ_{10} has proven stubbornly difficult to measure. A few years ago, results obtained at the Swiss Institute for Nuclear Research (now PSI) indicated that λ_{10} varied from (642 ± 27) /μs at 30 K to (317 ± 13) /μs at 300K.[6] These values were significantly less than the predicted value of 900/ μs [7] and showed a very surprising temperature dependence [6]. However, these results have since been retracted [2]. New results from LAMPF presented by Alan Anderson at this meeting show that λ_{10} is significantly larger than expected: greater than 1000 /μs. This may help to explain why hyperfine effects have been so elusive in μcf experiments.

Meanwhile, the rate of formation of d$t\mu$ molecules has been found [1,8] to depend strongly on temperature and density and on whether a tμ atom collides with a D_2 or a DT molecule (see Figure 2). These effects are reflected in the dependences seen in the muon catalysis cycling rate (Figure 1) and are consistent with the model of resonant dtμ formation developed by Ponamarev and collaborators.[9] Progress in measuring and understanding dtμ-formation has been rapid and gratifying for both theorists and experimentalists. It should be remembered that Ponomarev's predictions of fast, resonant dtμ formation were largely responsible for the renaissance of μcf research activity during the last few years. Furthermore, ideas on enhancing the dtμ-formation rate using lasers have recently been advanced by Hiroshi Takahashi [10].

We can conclude that reaction rates and the overall catalysis cycling rate are susceptible to further exploration, but that the rates are sufficiently fast to permit many hundreds of fusions during the muon lifetime. We turn our attention therefore to the question of muon-capture losses.

MUON-CAPTURE LOSSES (W)

Various ways in which muons may be lost from the catalysis cycle are shown in Figure 2. The muon may be captured and retained by a helium nucleus synthesized during dtμ, $dd\mu$, or ttμ fusion, with sticking probabilities ω_s, ω_d, and ω_t, respectively. In addition, small amounts (typically less than 1%) of protium are present, resulting in pdμ and ptμ fusion, with muon sticking probabilities ω_{pd} and ω_{pt}. The muon may also be scavenged by ambient helium in the hydrogen-isotope mixture, as indicated in Figure 2. All of these processes contribute to W, the total muon-loss probability per cycle [1]:

$$W \simeq \frac{q_{1s} C_d}{\lambda_{dt} C_t + \lambda_{dd\mu} C_d} (0.58 \lambda_{dd\mu} C_d \omega_d + \lambda_{pd\mu} C_p \omega_{pd} + \lambda_{d\mathrm{He}} C_{\mathrm{He}}) + \frac{1}{\lambda_{dt\mu} C_d} (\lambda_{tt\mu} C_t \omega_t + \lambda_{pt\mu} C_p \omega_{pt} + \lambda_{t\mathrm{He}} C_{\mathrm{He}}) + C_{\mathrm{He}} \omega_{\mathrm{He}} + \omega_s^{\mathrm{eff}}. \quad (3)$$

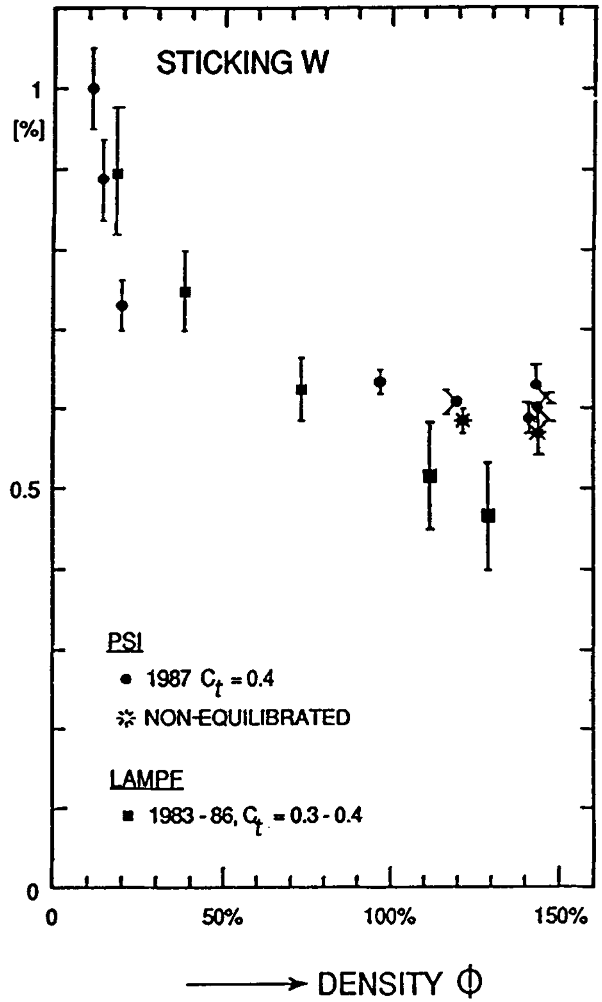


Figure 3. Data from LAMPF juxtaposed with the latest (1987) published results from PSI [11] show that the raw sticking W decreases with increasing density. Evidently, one or more muon-loss processes is density-dependent.

Experimentally measured values of W as a function of density are displayed in Figure 3. Results from LAMPF [1] and PSI [11] regarding the "raw sticking" W are in remarkable agreement and point to a rather striking density dependence.

What causes the obvious density-dependence of W? Looking closely at equation (4), we observe that some parameters such as $\lambda_{dt\mu}$ and possibly q_{1s} are significantly density-dependent, and in such a way that W will decrease with increasing target density, as observed. Until all muon-loss terms are fully understood, we cannot be certain whether ω_s, representing alpha-muon sticking following muon-induced d-t fusion and subsequent slowing down of the alpha-muon ion, is density-dependent or not [12]. In particular, if one assumes that q_{1s} is strongly density-dependent as predicted by Menshikov and Ponomarev [4], then one can account for much of the observed density-dependence of W. However, analysis of the LAMPF data has in fact shown only a weak density-dependence of q_{1s}, leaving a residual density-dependence in ω_s.[1] Thus, until q_{1s} and other interrelated parameters of equations (3) and (4) are sorted out completely, we cannot resolve this question. However, we can agree that W is indeed significantly density-dependent (Figure 3). After all, it is W rather than ω_s alone which influences the fusion yield (see equation 1).

DIRECT MEASUREMENT OF ALPHA-MUON STICKING

The data regarding W (Figure 3) were extracted by observing fusion neutrons, which results in a sensitivity to all processes which remove muons from the catalysis cycle. To measure ω_s alone, it is sufficient to count the number N of each of the charged products of the d-t fusion reaction, namely the α^{++} and $(\alpha\mu)^+$ ions:

$$\omega_s = \frac{N(\alpha\mu)}{N(\alpha) + N(\alpha\mu)} \tag{4}$$

Equation (4) expresses the muon loss fraction due only to $\alpha - \mu$ capture and retention following d-t fusion (note that ions are detected in coincidence with 14 MeV neutrons). Muon-stripping processes affect ω_s measured in this way, but complications stemming from competing dd and tt fusion channels, and muon scavenging by helium or other impurities (see Figure 2), can be excluded. Moreover, the ratio of equation (4) does not depend on absolute detector calibrations, a feature which reduces some systematic errors.

The experimental layout is portrayed in Figure 4 and is described in detail elsewhere (see ref. 13 and contributions by Michael Paciotti and John Davies, et al., in this volume). We recorded both the energy and the arrival time (relative to a fusion neutron) of each ion detected at the surface barrier

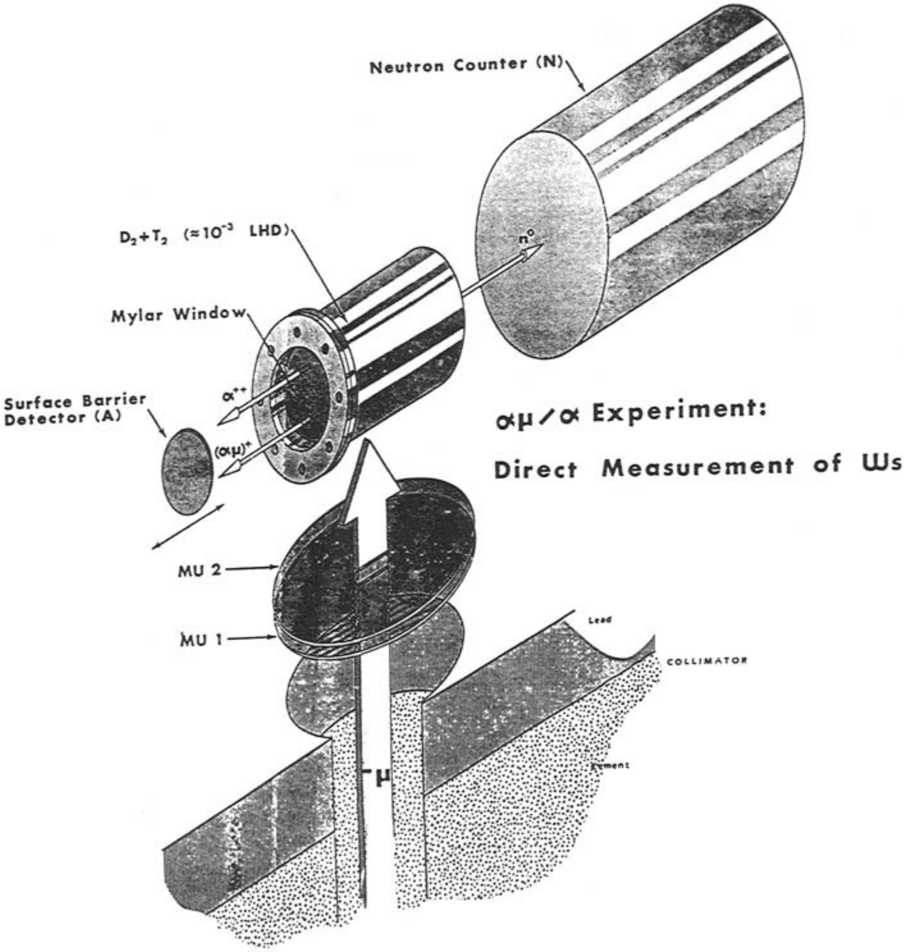


Figure 4. Scheme of the LAMPF/RAL experiment to measure alpha-muon sticking directly by detecting alpha and $(\alpha\mu)^+$ ions in coincidence with fusion neutrons.

detector. Figure 5 displays an energy spectrum of ions detected in a 10 nanosecond, neutron-coincidence time window chosen to select $(\alpha\mu)^+$ ions. A comparison with the same spectrum generated using Monte Carlo methods allows us to clearly identify both alpha and alpha-muon signals.

We are pleased to announce at this conference our first results obtained using this method. Data taken with a 60% deuterium - 40% tritium mixture at a pressure of 640 Torr are shown in Figure 5. At this pressure, we observe both alpha and alpha-muon signals. We need to correct the observed number of alpha particles for the fraction whose energy falls below the detection threshold (0.7 MeV) before reaching the detector (about half in this case, depending on the set position of the surface-barrier detector). Also, the number of detected alpha-muon ions must be corrected for the fraction lost due to stripping in the mylar window (8.3%) and in the gas (7.8%) before reaching the detector. These corrections are determined with the use of two separate Monte Carlo codes, which agree to within about 3%. The result for the <u>initial</u> sticking probability ω_s^o for data taken at LAMPF at a pressure of 640 Torr is:

$$\omega_s^o = (1.2 \pm 0.2 \pm 0.1 \quad \text{systematic})\% \quad (640 \quad \text{Torr, preliminary}) \tag{5}$$

In order to gather better statistics, we separately collected alpha-muon ions at 1800 Torr and alpha ions at 490 Torr. This method is described in detail in Mike Paciotti's contribution in this volume. The result obtained in this way is:

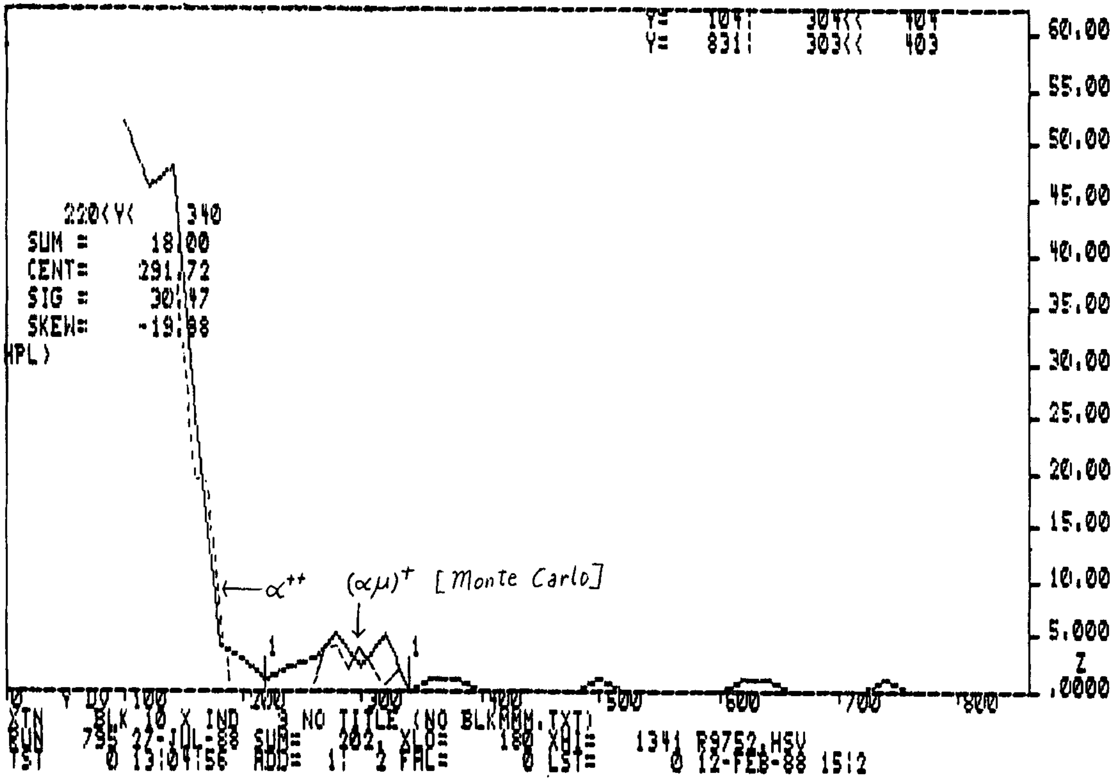
$$\omega_s^o = (0.80 \pm 0.15 \pm 0.12 \quad \text{systematic})\% \quad (490 \quad \text{and} \quad 1800 \quad \text{Torr, preliminary}) \tag{6}$$

While the statistics are better in this case, the estimated systematic error is large due mainly to uncertainty in the scaling of the fusion yield with the change in density [14]. It could well be that the fusion yield scales other than linearly with increasing density as assumed to obtain (6). This effect could then pull results (5) and (6) of the two approaches into better agreement. The measurements will be refined in future experiments at Rutherford Laboratory.[15]

We can already draw two important conclusions from these new results. First, the measured initial alpha-muon sticking probability appears to be in reasonable agreement with published theoretical calculations [16,17]:

$$\omega_s^o = (0.88 \pm 0.05)\% \quad (\text{theoretical}). \tag{7}$$

Figure 5. Energy spectrum of ions detected at LAMPF in a time window chosen to select $(\alpha\mu)^+$ ions. Juxtaposition with the same spectrum generated by simulating the experiment using Monte Carlo methods (dashed line) allows us to clearly identify α^{++} and $(\alpha\mu)^+$ signals in the data.



(See Mel Leon's paper in this volume for further discussion of recent of theoretical work on alpha-muon sticking.) Secondly, the directly measured value of sticking evidently rules out the possibility that sticking is very small (less than say 0.25%; see ref. [18]).

Before the measurement was made, one could argue that some process not included in equation (3) was making W large, while the sticking term ω_s^o was actually small. It is now clear that the initial sticking is large, around 1%, and that muon stripping as the alpha-muon ion slows down in the gas (density-dependent regeneration R) reduces this value very significantly:

$$\omega_s = \omega_s^o(1 - R \quad [density - dependent]) \tag{8}$$

Figure 6 displays the predicted [16] density-dependences of R and ω_s along with the (weighted) average value of ω_s based on measurements taken at LAMPF [1], PSI [8,19], and KEK [20] in liquid d-t mixtures. The separate measurements all agree within experimental errors. Note that the high-density value for sticking ω_s is about half the initial-sticking value. Significantly, we find that there remains some discrepancy between the experimental and theoretical values for sticking ω_s at liquid hydrogen density.

We have made considerable progress in understanding the alpha-muon sticking probability and related muon-loss mechanisms, but more work is clearly needed. It is also clear that sticking is the major bottleneck in the muon catalysis cycle, probably limiting the yield to a few hundred fusions per muon even at high densities.

EXPECTED FUSION YIELDS AND CONCLUSIONS

Since the catalysis cycling rate λ_c increases whereas the overall muon loss probability W decreases with increasing d-t density, we expect from equation (1) that the fusion yield will grow rapidly with increasing density. This is indeed the case, as demonstrated in Figure 7. In fact, the observed yield exceeds theoretical expectations of a few years ago by a comfortable margin.

But is it enough? Yuri Petrov has shown [21] that a hybrid reactor using μcf in conjunction with fission processes could generate power commercially when the μcf yield reaches about 150 fusions per muon. Figure 7 shows that this level has been reached in experiments. However, I suspect that fusion-fission hybrid reactors will remain unattractive as long as uranium remains inexpensive, particularly since hybrids partake of many of the problems of conventional fission reactors.

To produce power commercially using μcf alone would probably require

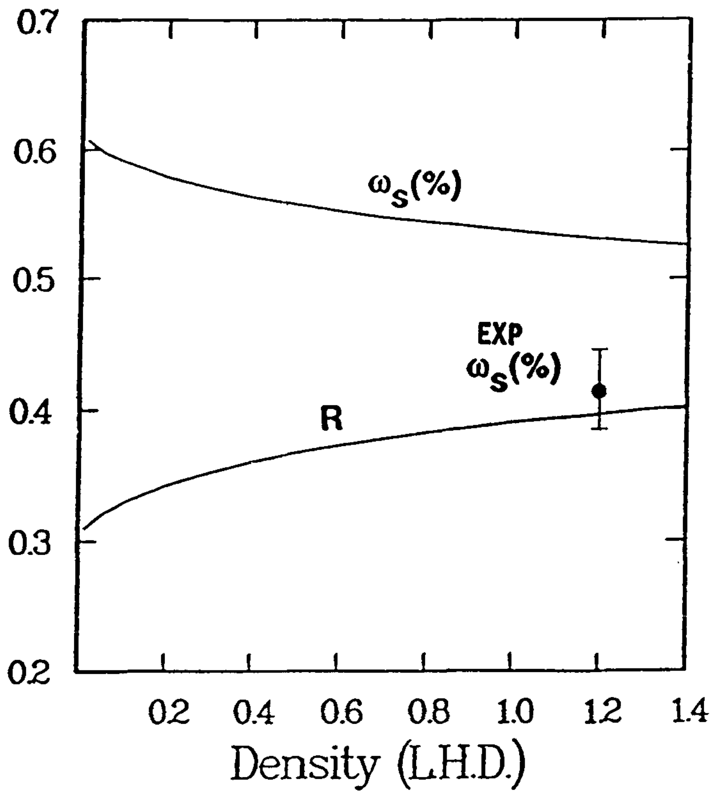


Figure 6. Calculated alpha-muon sticking ω_s assuming an initial sticking of 0.88% and regeneration R versus density [16], along with the observed sticking in liquid d-t mixtures (averaged from LAMPF, PSI and KEK experiments).

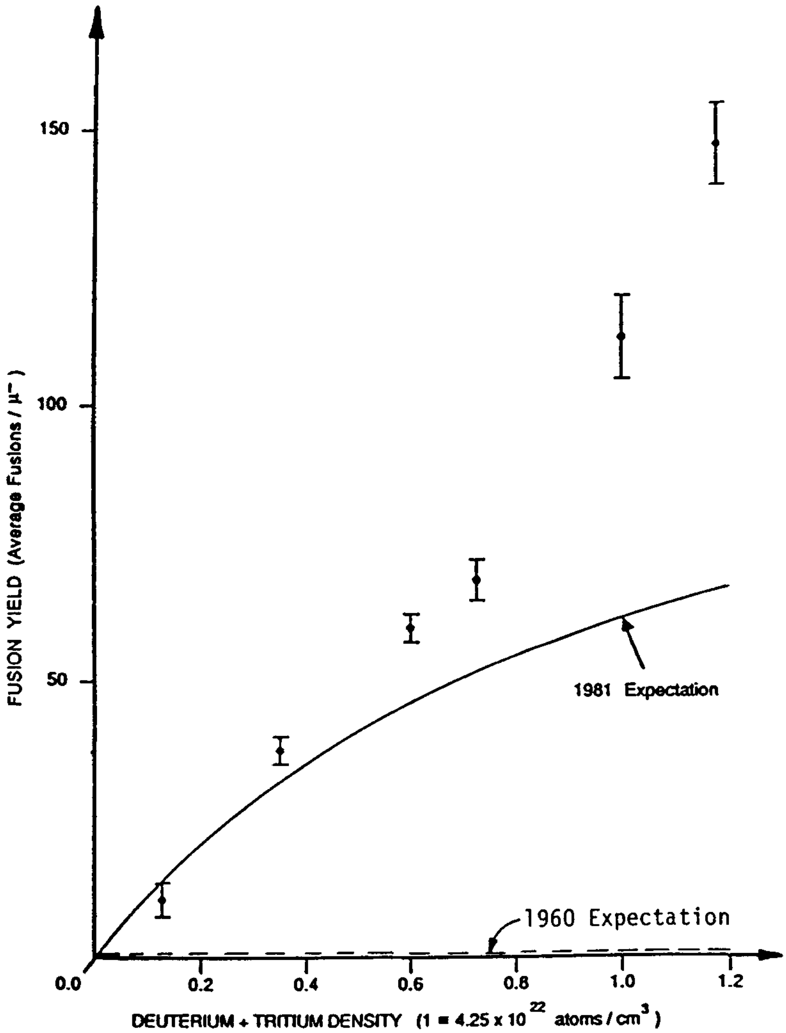


Figure 7. The average number of muon-catalyzed d-t fusion cycles ovserved by the BYU/Idaho/Los Alamos collabration as a function of density, for cold ($T < 100K$), equimolar deuterium-tritium mixtures. Note that the observed yield exceeds theoretical predictions at high densities.

an order-of-magnitude increase in the yield per muon, assuming current technology for muon production. Such a jump seems unlikely now because of the barrier imposed by alpha-muon sticking. However, some clever "imagineering" concepts were advanced at the workshop. For instance, Kulsrud and Tajima proposed a design in which alpha-muon ions would be repeatedly accelerated through solid d-t ice cells, to shake loose the muon (see paper by Kulsrud and Tajima in this volume). This concept appears to replace the sticking bottleneck with a very challenging engineering problem. In a paper presented at the workshop by Ponomarev, L. I. Men'shikov proposes that a cool plasma could greatly reduce the sticking coefficient [22]. Maintaining a sufficiently large $dt\mu$-molecular formation rate under such conditions would, they warn, be challenging.

In my opinion, the energy cost of producing muons must be very substantially reduced before energy production by means of μcf could be seriously considered. However, the field is young and active, and I think that such speculations are basically healthy as we vigorously strive to understand the beautiful phenomenon of muon-catalyzed fusion.

ACKNOWLEDGEMENTS

Discussions with numerous μcf colleagues have contributed to this summary. I particularly acknowledge valuable input from Alan Anderson, Antonio Bertin, Gus Caffrey, Jim Cohen, John Davies, Mel Leon, Ken Nagamine, Michael Paciotti, Claude Petitjean, Yuri Petrov, Leonid Ponomarev, Jan Rafelski, Antonio Vitale, and Alexi Vorobyov.

This research is supported by the Advanced Energy Projects Division of the U.S. Department of Energy.

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