μCF

Muon Catalyzed Fusion

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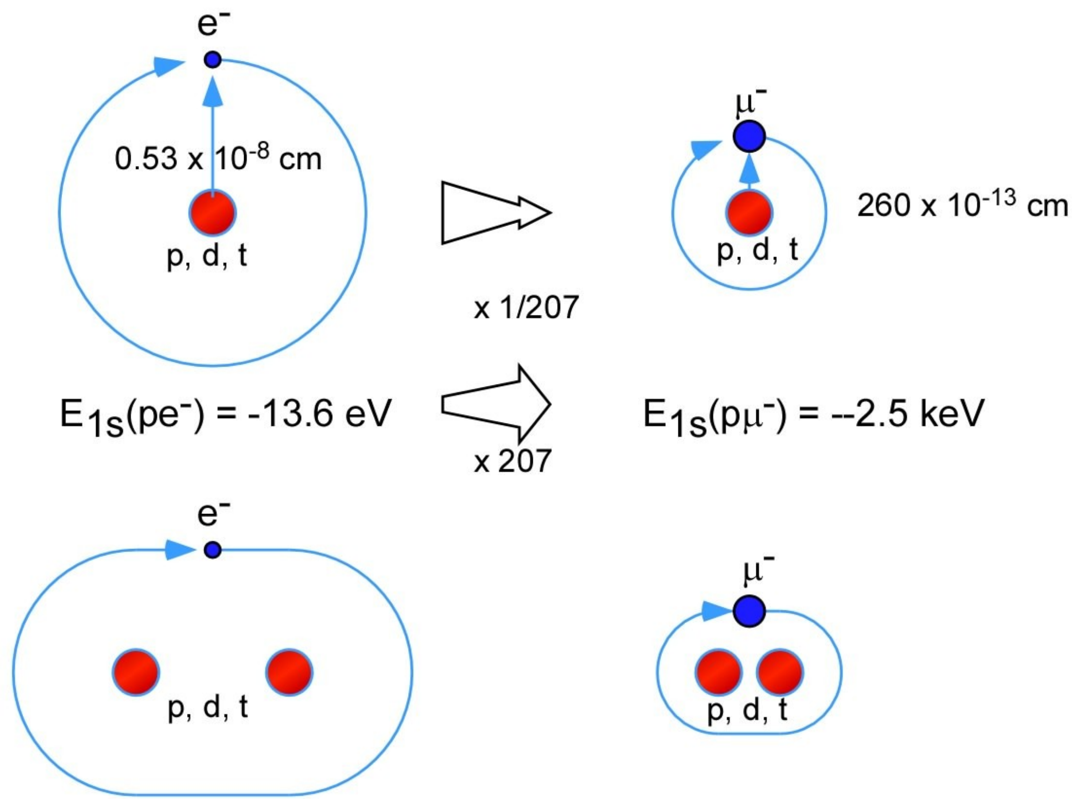
9 June 2025

μCF Principle

Normal hydrogen atom/molecule vs Muonic atom

Future muon sources,
Huddersfield,UK 13 Jan 2015
K.Ishida (RIKEN)



$\beta_{g.s.}(ppe^-) = 2\, a_{1s}(pe^-) = 1.1 \times 10^{-8}$ cm

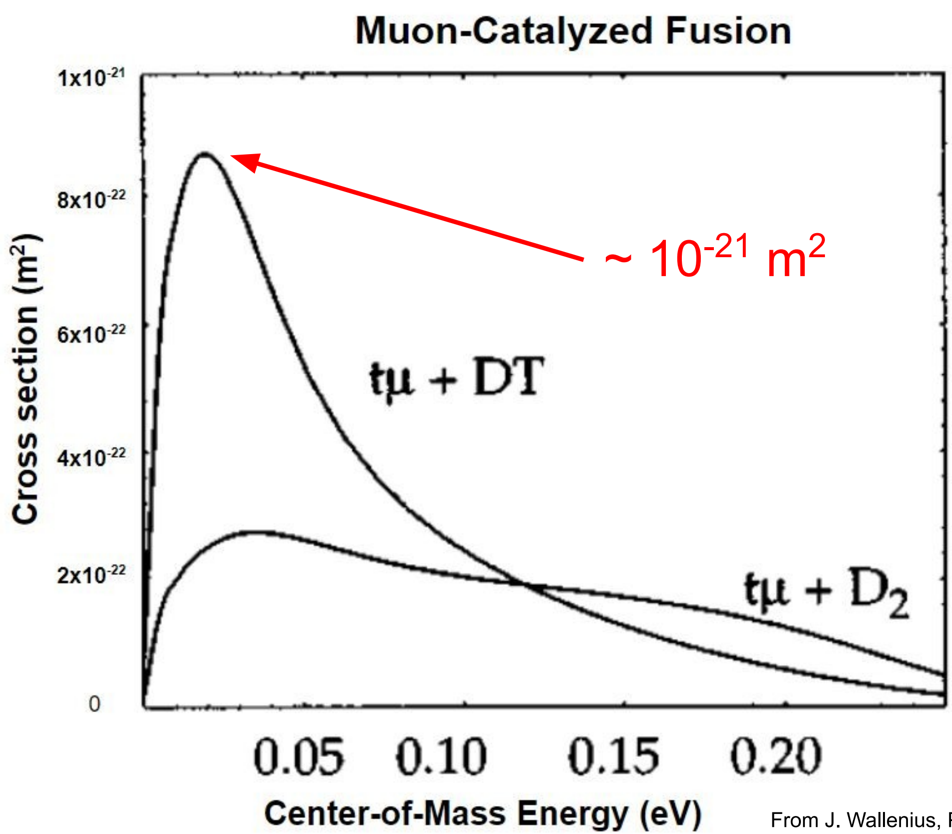
$Eg.s.(ppe^-) = 1/10\, E_{1s}(pe^-) = -1.4$ eV

$\beta_{g.s.}(pp\mu^-) = 520 \times 10^{-13}$ cm

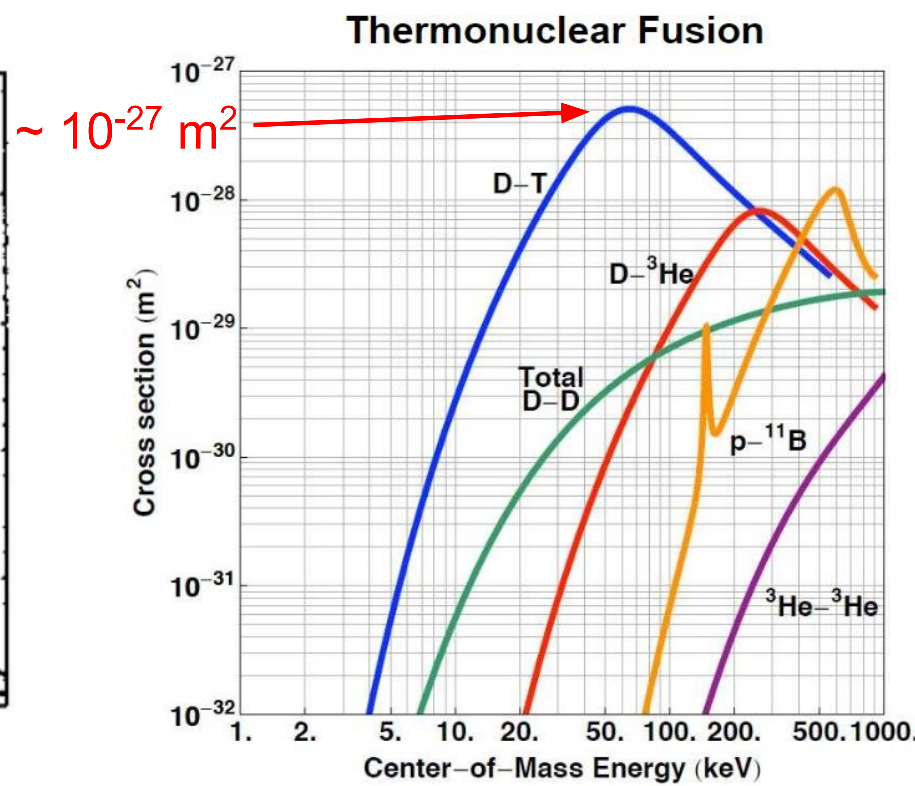
$E_{g.s.}(pp\mu^-) = -250$ eV

BV52, PSI, 2021
A.Knaian, K.Lynch

muCF is interesting because of large cross section



From J. Wallenius, P. Froelich, Formation of metastable dtmu molecules in tu(2s)-D2 collisions, Physical Review A, Vol 54, No. 2, 1996



From Wikimedia Commons

μCF Cycle

After injection of muons into D/T mixture

Formation of muonic atoms and molecules

d-t fusion in small dtμ molecule

muon released after d-t fusion

- muon works as catalyst –

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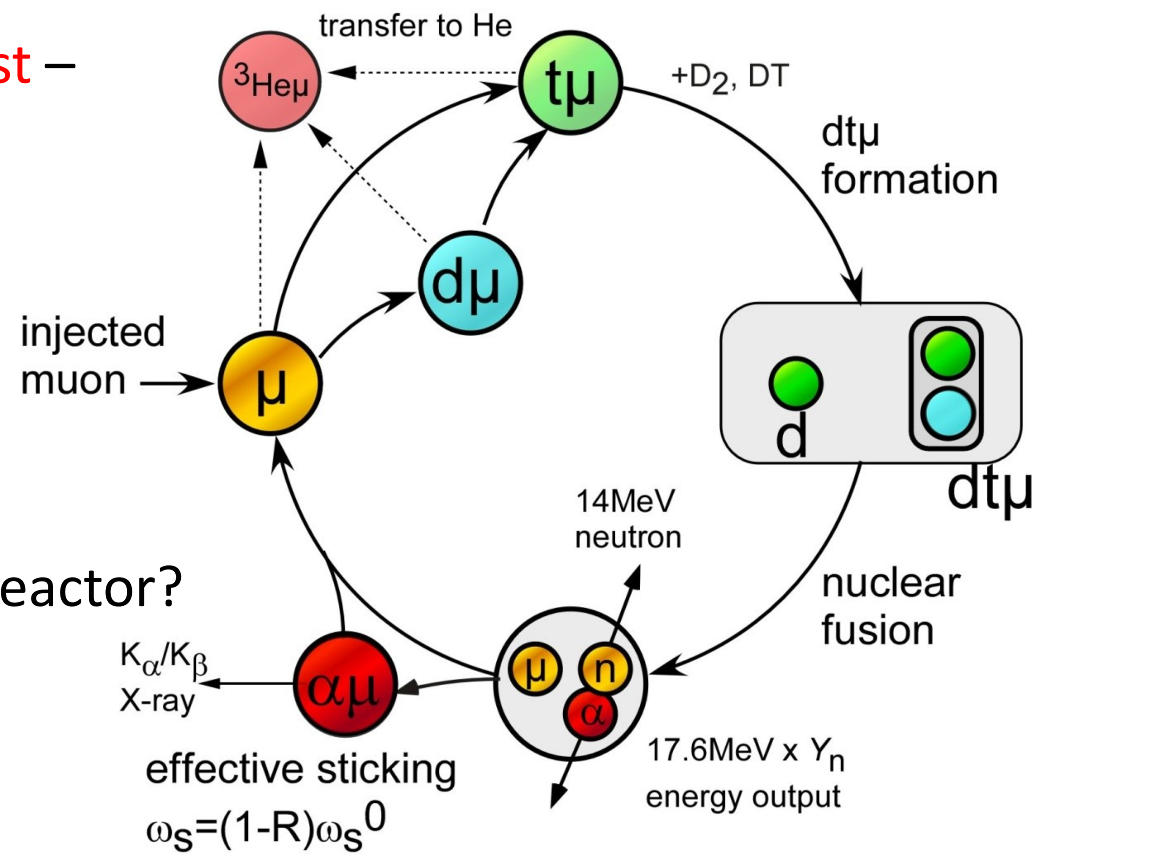
Rich in few body physics.

Can we consider a MuCF reactor?



MuCF cycle

Cycle rate ~ few 100 μs^{-1}

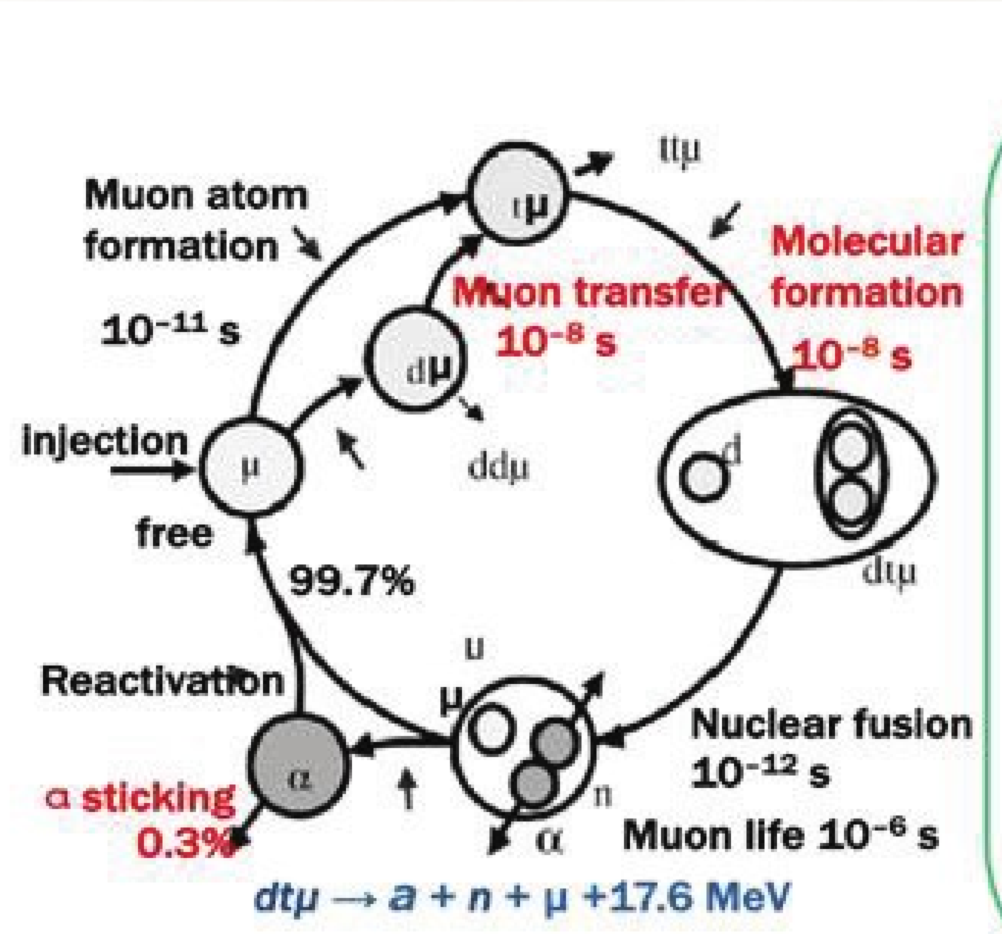
compared to muon lifetime = 0.45 μs^{-1}

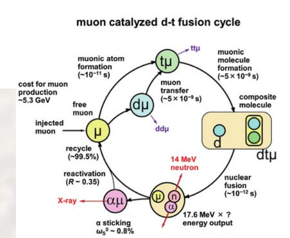
Muon α-sticking loss ~ 0.5%

100-200 dt fusions/muon

Depends on T,P, density, solid/gas, d/t mixture, etc

at liquid hydrogen density (LHD)





Key process of μCF(1) - dtμ formation

Making bound state

by removing surplus energy (is not so easy)

Auger process

$t\mu + D_2 \rightarrow (dt\mu) + D + e^-$

dissociate molecule by removal of electron

too slow for fusion (2×10^{-6} s)

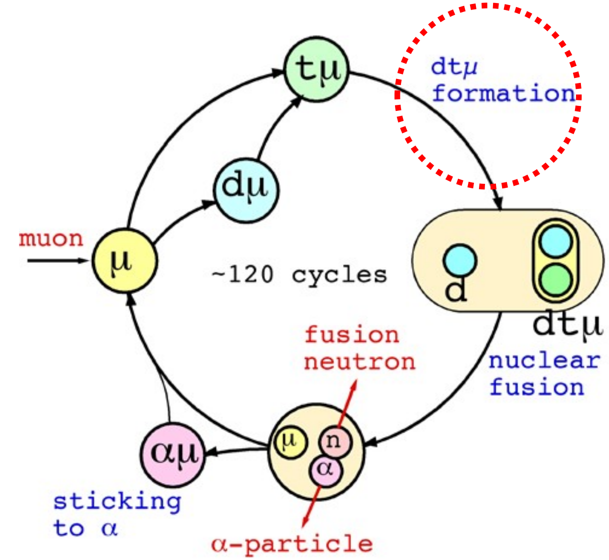
Observation of unexpected fast and temperature dependent rate at Dubna (1975)

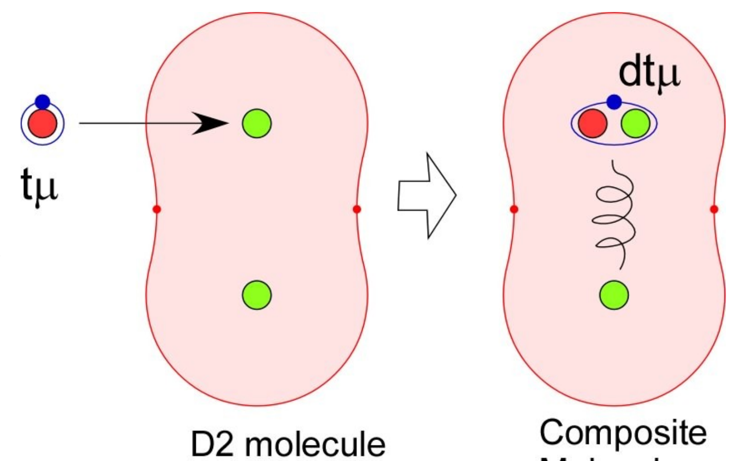
Resonant formation was proposed

Presence of shallow bound state in ddμ、dtμ

$t\mu + D_2 \rightarrow [(dt\mu)Dee]$

Even a small energy difference matters (temperature, molecular state)





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Key processes of μCF (2)
μ-to-α sticking

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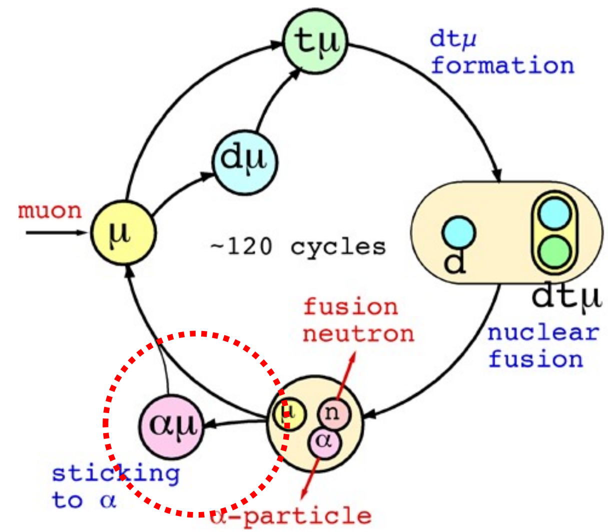
Some of the muons may follow the recoiling a–particle after dt-fusion with small but non-negligible probability ω_s^0,

$$d t\mu \;\xrightarrow{1-\omega_s^0}\; \alpha + \mu + n$$

$$d t\mu \;\xrightarrow{\omega_s^0}\; \alpha\mu\ (3.5\ \mathrm{MeV}) + n$$

$$\alpha\mu\ (3.5\ \mathrm{MeV}) \;\xrightarrow{R}\; \alpha + \mu$$

$$\alpha\mu\ (3.5\ \mathrm{MeV}) \;\xrightarrow{1-R}\; \alpha\mu\ (\mathrm{thermal})$$



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

ω_s^0 is an intrinsic value determined only by local atomic parameter

$\omega_s^0\,(nl) = \sum |F(nlm)|^2$, $F(nlm) = \int \phi_{nlm}(r)\, e^{-iqr}\, \psi_{in}(r)\, dr$

with powerful few body calculations ω_s^0 = 0.9%

R (~0.3) can be dependent on target condition

ω_s place limit on the number of fusions

R~0.35 for high densities

Latest most precise calculation:
M.Kamimura et al,
Phys. Rev. C 107, 034607 (2023)
ω_s^0 = 0.857%
ω_s = 0.557% ⇨ Y^{max} ~ 180 cycles

Additional stripping by μHe+ acceleration:
Y.Mori , Prog. Theor. Exp. Phys. 2021, 093G01 (2021)

Maximizing μCF efficiency

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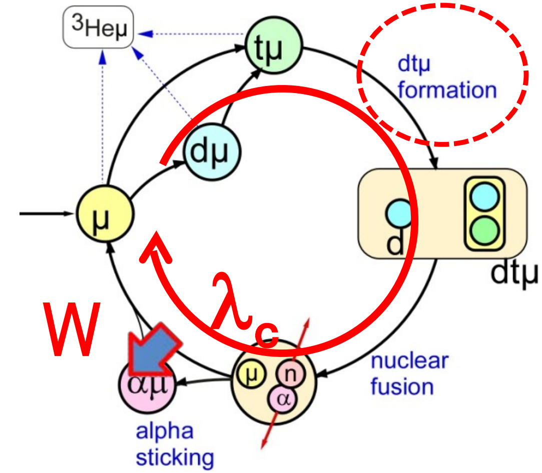
To increasing muCF rate

Cycling rate λ_c (↑) (vs λ_0: muon life)

dtμ formation : tμ + D_2 →[(dtμ)dee]

Muon loss per cycle W (↓)

muon sticking to α-particle, etc

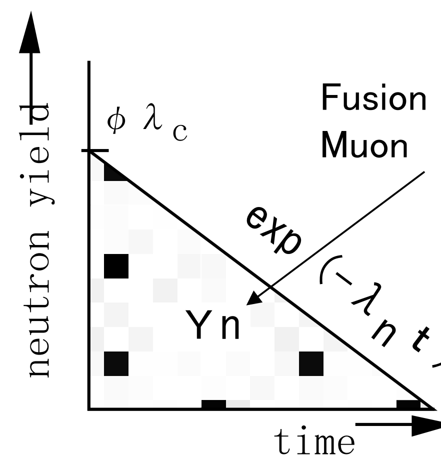


Fusion neutron disappearance rate :

$$\lambda_n = \lambda_0 + W\phi\lambda_c$$

Number of fusion per muon:

$$Yn = \phi\lambda_c/\lambda_n = 1 / [(\lambda_0/\phi\lambda_c)+W] \; (\uparrow)$$



DT target conditions matter:
Temperature, pressure, density, solid,
molecular state etc

Theoretical aspects

Figure 20. The scheme of muon catalysed fusion processes in a D_2+T_2 mixture.

muon stripping processes and cascade transitions in mesic atoms and mesic molecules are taken into account. In the description of the μ-catalysis resonant process, the various processes of elastic and inelastic scattering of mesic atoms, whose cross-sections also display a rather spectacular dependence on collision energy, should be taken into account at the same time.

of the medium (T, φ, c, etc.). At present various experimental installations have been designed that make possible the observation of practically ... of μ-catalysis reactions: the neutrons of ... and the dependence of their yield on time dN_n/dt (JINR, LAMPF, PSI, RAL, TRIUMF); α-particles and mesic ions $(\mu He)^+$ from reactions (24 *b*) and (26 *b*) (LNPI, LAMPF, PSI, RAL); γ-... reactions (7 *b*) and (32 *b*); also ... transitions in $(\mu He)^+$ and in ... change reaction (23 *b*) (PSI, KE... muon depolarization rate in spin-... (JINR); the decay $\mu^- \to e + \tilde{\nu}_e + \nu_\mu$ in all μ-catalysis processes.

Muon catalyzed fusion, L.I. Ponomarev
Contemp.Phys. 31 (1990) 219-247

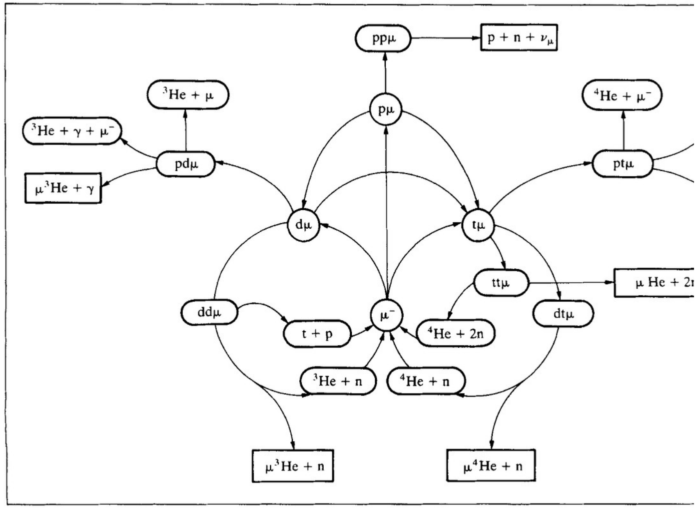


Figure 21. The scheme of μ-catalysis processes in the triple mixture $H_2+D_2+T_2$.

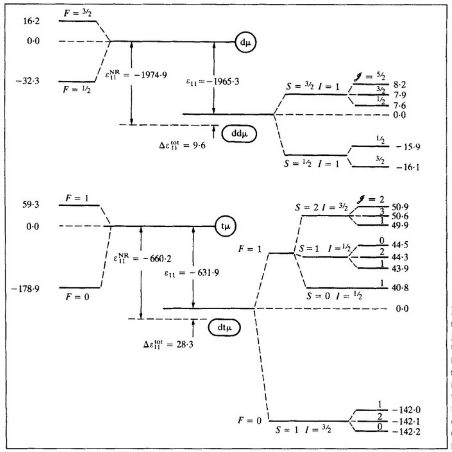


Figure 13. The fine a... splitting schemes of the ... μ molecule states (J = ... the atom total spin, S ... molecule total spin, I ... spin of nuclei, $\mathcal{J} = S + ...$ momentum of the syst... the angular momentum ... ues are given in meV, ... calculations of Bakalov (1989) (see also table ... meV).

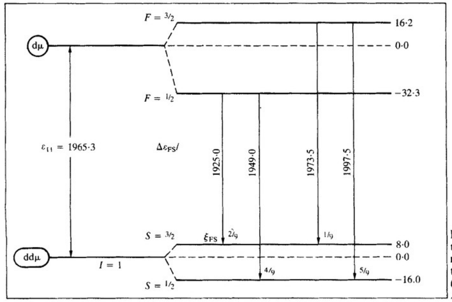


Figure 14. The sche... tions in process (26 *c*) ... resonant formation. At ... tures $T \approx 30$ K the ... $(F=3/2) \to i$ $(S=1/2$ ... All values are given in ...

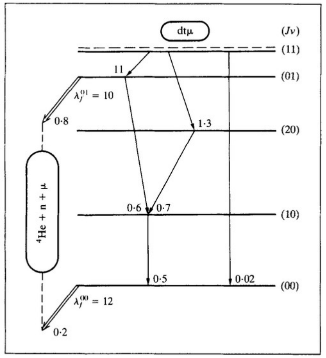


Figure 18. The scheme of cascade transitions in the mesic molecule dtμ, formed in state ($J=v=1$) in the resonant reaction (24 *b*). All rates are in 10^{11} s^{-1}.

From the states $J=1$;

$$\lambda_f = B|\nabla\psi_m(0)|^2 \qquad (31\,a)$$

where $\psi_m(R)$ is the mesic molecule wave function, R is the internuclear distance, A and B are constants of the nuclear reactions (6 *b*) (scattering state $J=0$) and (6 *a,c*) ($J=1$) respectively.

In table 5 the results of the calculations of fusion rates in the different mesic molecules in states (Jv) are presented. (The fusion rate in the mesic molecule ppμ is negligibly small in comparison with λ_0).

The reactions in mesic molecules can proceed from different states (Jv) via different channels (in table 5 the rates of the dominant channel are given)

$$dd\mu \longrightarrow \begin{cases} {}^3He + n + \mu^- & (32\,a) \\ \mu^3He + n & (32\,b) \\ t + p + \mu^- & (33\,a) \\ t\mu + p & (33\,b) \end{cases}$$

$$pt\mu \longrightarrow \begin{cases} {}^4He + \mu^- & (34\,a) \\ \mu^4He + \gamma & (34\,b) \\ \mu^4He + e^+ + e^- & (34\,c) \end{cases}$$

$$pd\mu \longrightarrow \begin{cases} {}^3He + \mu^- & (35\,a) \\ \mu^3He + \gamma & (35\,b) \end{cases}$$

In the mesic molecule ddμ for example, reactions (32 *a*) and (32 *b*) are by a factor of about 1·5 more probable than (33 *a*) and (33 *b*); the probability of reaction (35 *a*) in the mesic molecule pdμ is only ~14% and the relation of channel probabilities of reaction (34) in the mesic molecule ptμ is still the subject of investigations.

The relation of cascade transitions to nuclear reactions leads to the fact that in the dtμ molecule, nuclear reactions proceed from states (01) and (00) with probabilities 0·8 and 0·2 respectively. The fusion rate from the initial state (11) is small (~10^7 s^{-1}), and the probability of muon loss due to its decay in the cascade process and due to nuclear reaction in the dtμ molecule is also negligibly small ($\leqslant 10^{-5}$).

4.10. MUON STICKING AND STRIPPING

In the channels of reactions (32 *b*), (34 *b*) and (35 *b*) the muon in the final state of the nuclear reaction 'sticks' to the helium nucleus and is lost for further catalysis cycles; 'catalyst poisoning' occurs. The probability of muon sticking in a state (nl) of the mesic atom $(\mu He)_{nl}$ in nuclear synthesis from the mesic molecular state (Jv)

Table 5. Synthesis reaction rates λ_f^{Jv} in units of s^{-1} from mesic molecule states (Jv)†

Molecule	State (00)	(01)	(10)	(11)	(20)	(30)	Experiment
pdμ	8×10^5	–	–	–	–	–	3×10^5
ptμ	$\leqslant10^6$	–	–	–	–	–	0.7×10^5
ddμ	–	–	$1{\cdot}5\times10^9$	$4{\cdot}3\times10^8$	–	–	$4{\cdot}1\times10^8$
dtμ	$1{\cdot}2\times10^{12}$	$1{\cdot}0\times10^{12}$	–	–	–	–	–
ttμ	–	–	$1{\cdot}3\times10^7$	$1{\cdot}2\times10^7$	–	–	$1{\cdot}5\times10^7$

† The experimental data are given for orientation without the proper analysis of the results from different groups. The theoretical values are compiled according to the paper by Bogdanova (1988).

Multi body, mixtures, different reactions,
Transitions from different excited states,
resonance cross-sections….
Complete picture is quite complicated

Present Status and Outstanding Problems

Future muon sources,
Huddersfield,UK 13 Jan 2015
K.Ishida (RIKEN)

d$t\mu$ Molecular Formation

Resonant mechanism was basically established

$\lambda_{dt\mu}(\phi$, T, E, Ct,...) - very much dependent on condition

puzzles and surprises

(three-body, epithermal, non-equilibrium)

Muon-to-Alpha Sticking

Initial Sticking (0.9%) - hard to modify

Muon Reactivation - final sticking, $K\beta/K\alpha$ ratio puzzle

Best conditions for μCF (several directions)

Solid D/T (high density) (Y_n~120 @PSI,RAL)

Non-equilibrium D/T (Y_n~124 @PSI $t\mu+D_2$, ortho/para@RIKEN)

High temperature - high density (Y_n=150? @LAMPF,Dubna)

Epi-thermal $t\mu$ (TRIUMF)

μCF History

Future muon sources,
Huddersfield,UK 13 Jan 2015
K.Ishida (RIKEN)

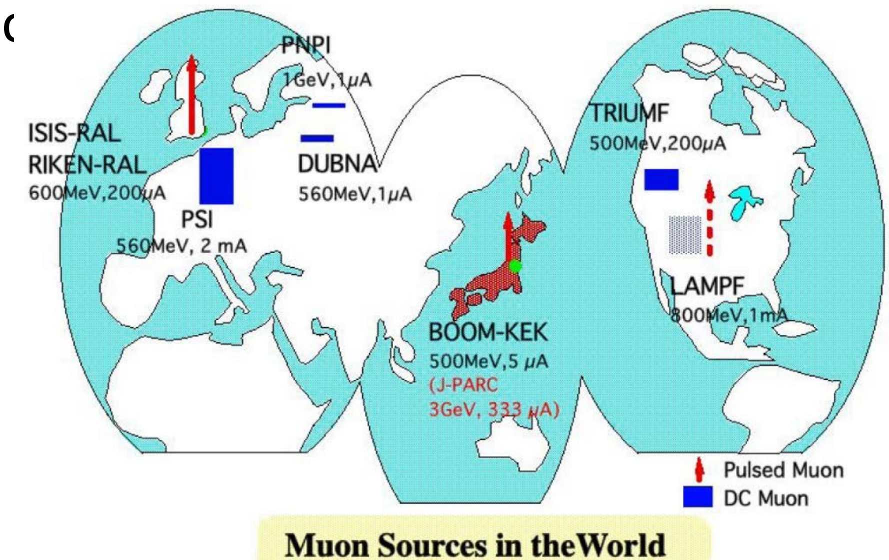
1936 Discovery of muon

1947 Idea of MuCF (F.C. Frank), 1948 (A.D. Sakharov)

1956 First observation of muon induced fusion (Alvarez in bubble chamber)
(1957 Discovery of parity-violation)

1977 Prediction of fast molecular formatic

1982- Observation of large dt fusion rate
Studies in Dubna, LNPI, LAMPF, PSI,
TRIUMF and
KEK (1986-)
RIKEN-RAL (1996-) -2003



NobelP Luis Alvarez discovered muon catalyzed fusion in the 1956, which was studied with renewed interest in the '70s and '80s.

Atomic Energy Produced By New, Simpler Method

Coast Scientists Achieve Reaction Without Uranium or Intense Heat—Practical Use Hinges on Further Tests

Special to The New York Times

MONTEREY, Calif., Dec. 28—A third and revolutionary way to produce a nuclear reaction was described here today. It does not involve uranium, as in the fission reaction, or million-degree heat, as in the fusion reaction.

The new process is called "catalyzed nuclear reaction." It was discovered accidentally a few weeks ago during routine work with the huge atom-smashing bevatron at the University of California radiation laboratory.

A team of twelve scientists from the university explained the process to the American Physical Society here. The team was headed by Dr. Luis W. Alvarez, assistant director of the laboratory.

Curiously enough, it was made not at the laboratory at Livermore, where scientists are attempting to control thermonuclear reaction for practical uses, but at the Berkeley laboratory, which is devoted to fundamental research.

Thus far, the new reaction is little more than a laboratory curiosity, the scientists said. The energy it produced came from the fusion of a few hydrogen atoms, they explained, and was scarcely enough to register on highly sensitive measuring instruments.

The process has no commercial value now, though it suggests possible industrial uses of immeasurable importance. It may, scientists said, point a way toward taming the intense heat of the hydrogen bomb to make it useful for peacetime purposes.

Others in the University of California group were Dr. Hugh Bradner, Dr. Frank S. Crawford Jr., Dr. John A. Crawford, Dr. Paul Falk-Vairant, Dr. Myron L. Good, Dr. J. Don Gow, Dr. Arthur H. Rosenfeld, Dr. Frank Solmitz, Dr. M. Lynn Stevenson, Dr. Harold K. Ticho and Dr. Robert D. Tripp.

One method of obtaining nuclear reaction—the so-called "fission reaction" employed in the atom bomb—relies on the bombardment of atomic nuclei with other atomic particles.

The other—the "thermonuclear reaction" of stars and the modern hydrogen bomb—depends upon the union or fusion of two light atomic nuclei to form one heavy nucleus at temperatures of about 1,000,000 degrees.

The type described today employs a medium-weight atomic particle (known as a negative mu-meson) as a catalyst to make a hydrogen nucleus fuse with a deuterium (heavy hydrogen) nucleus. This fusion occurs at low temperatures.

One result is the formation of helium—a variety known as helium-3. Another is the release of prodigious amounts of energy, calculated at about 5,400,000 electron volts for each reaction.

The mu-meson, which triggers this change of elements, is not used up as a catalyst, but remains free to bring together other nuclei of hydrogen and deuterium, and form more helium-3 and produce more energy.

Catalyst Short-Lived

But the catalyst is extremely short-lived, Dr. Alvarez noted, and thus limits the process. The mu-meson has a life of approximately one-millionth of one second, a period sufficient to let it catalyze no more than one or two fusions before it perishes.

In commenting on the future of the new reaction, Dr. Alvarez said:

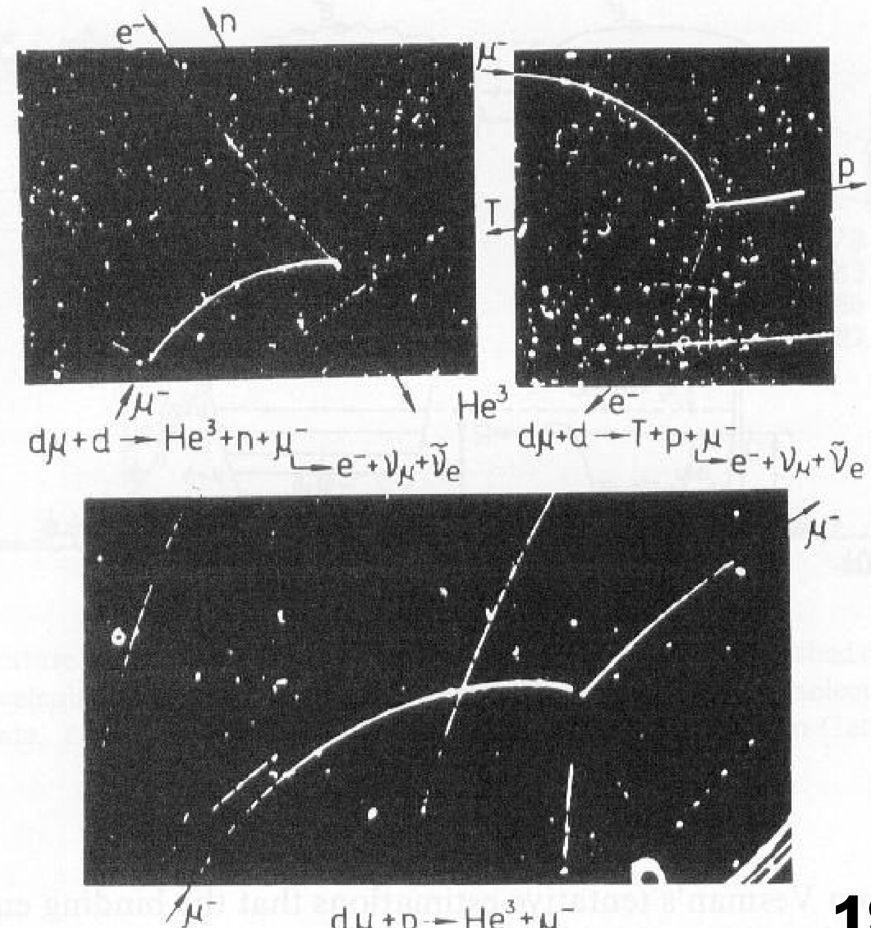
"If this is to become of practical importance, we would have to find a different catalyzing particle which has properties similar to the mu-meson but has a lifetime of at least ten or twenty minutes."

Such a particle would permit millions of energy-producing reactions and, it may be presumed, the release of enough energy to operate electric generators, motors and other heavy equipment.

In this connection, Dr. Alvarez—who recently traveled through the Soviet Union and visited scientific laboratories there—observed:

"It is interesting that Russian scientists have reported evidence that such a particle does exist in cosmic rays."

The announcement of the discovery of the "catalyzed nuclear reaction" was made simultaneously by the Atomic Energy Commission in Washington. The commission provides financial support for the fundamental research at the Berkeley Atomic Laboratory.



1957

MuCF review papers:

Muon-catalyzed fusion, W.H. Breunlich, P. Kammel, J.S. Cohen, M. Leon
Ann.Rev.Nucl.Part.Sci. 39 (1989) 311-356

Muon catalyzed fusion, L.I. Ponomarev, Contemp.Phys. 31 (1990) 219-247

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Annu. Rev. Nucl. Part. Sci. 1989. 39: 311–56

MUON-CATALYZED FUSION

W. H. Breunlich and P. Kammel

Institute for Medium Energy Physics, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria

J. S. Cohen and M. Leon

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Very hot-topic in 70's-90's

After work by Gershtein & Ponamarev in 1977
predicts x100 catalyzed dt fusions/muon

A lot of theoretical efforts: 3 body problem, molecular, ...

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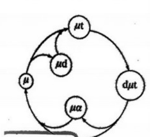
VOLUME 7 (1992)
No. 4
ISSN 0259 9805
Published December 1992



MUON CATALYZED FUSION

Editors-in-Chief:
L.I. Ponomarev - C. Petitjean

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MUON CATALYZED FUSION

SCOPE OF THE JOURNAL:
Muon catalyzed fusion has become a high lighted research field since the discovery of high cycle rates for dt-fusion induced by muons and hopes for future applications of "cold fusion". This Journal is devoted to μCF-physics and related topics; mesic atomic and mesic molecular physics, interdisciplinary methods involved in μCF-studies, μCF-applications as a research method and a possible practical use for the energy production. The Journal will publish the contributions in the theory and experiment, especially in the context with conferences.

The Journal will be exacting and scholarly in its standards. Every effort will be made to promote innovation, vitality and communication between disciplines.

All papers will be refereed. There will be no page charge. A total of 25 free reprints per paper will be available free of charge. Additional reprints can be ordered from the Publisher at the normal prices of the journal.

SUBSCRIPTION INFORMATION:
MUON CATALYZED FUSION will be published in volumes of 4 issues. For 1992 one volume has been announced. The subscription price for 1992 (Vol. 7) is: Swiss Francs 356.50, postage included.

Subscriptions should be sent to the Publisher: J.C. BALTZER AG, SCIENTIFIC PUBLISHING COMPANY, Wettsteinplatz 10, CH - 4058 Basel, Switzerland, or to any subscription agent or bookseller.

PRINTED IN THE NETHERLANDS BY VE & ES DEVENTER BV

Dedicated journal
1987 - 1992

μCF in laboratories

Dubna

observation of temperature effect (resonant formation)

LAMPF

First observation of *Y*n>120 high-density D/T

PSI

process in various low density mixtures

$\alpha\mu$ ion detection, ...

TRIUMF

tμ atomic beam

KEK

α-sticking x-ray, muon transfer to He

RAL

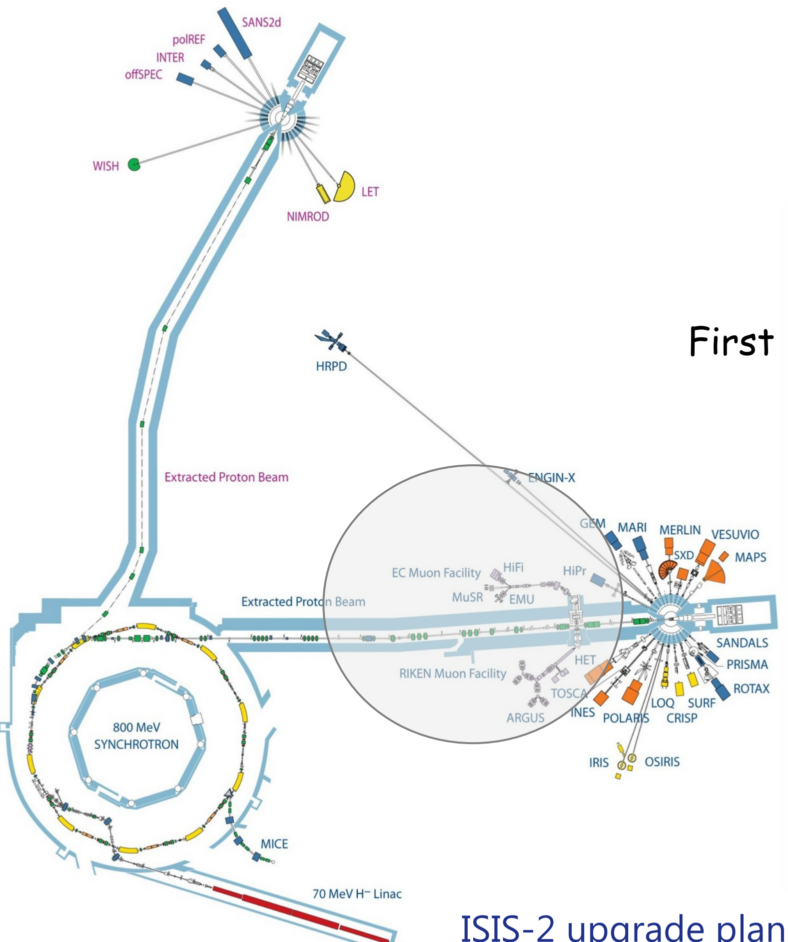
α-sticking x-ray ,

fusion in various mixtures, ...

Muons at ISIS

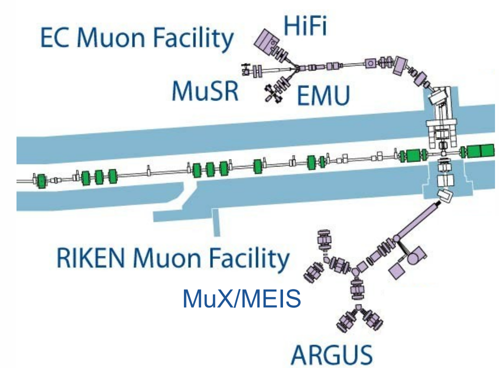
STFC Rutherford Appleton Laboratory, UK

Adrian Hillier, Muon4Future 2025



Muons Instruments at ISIS

First muons at 1987



~ 10^6 muon/sec

Science and Technology Facilities Council

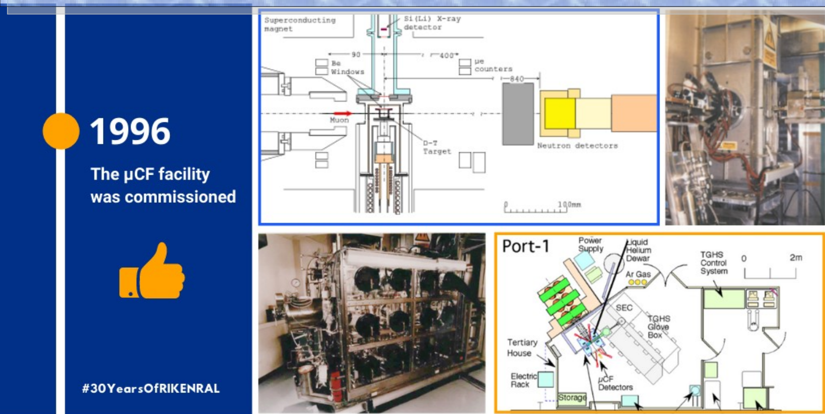
EC Muons
Fixed Momentum Muons ~27MeV/c
Positive muons
Longitudinal fields upto 5 T
Transverse fields upto 600+ G (pulse width limited)
Temperature range 30mK – 2000K
Laser excitation
Pulsed techniques e.g. RF, EF, Light, ac susceptibility

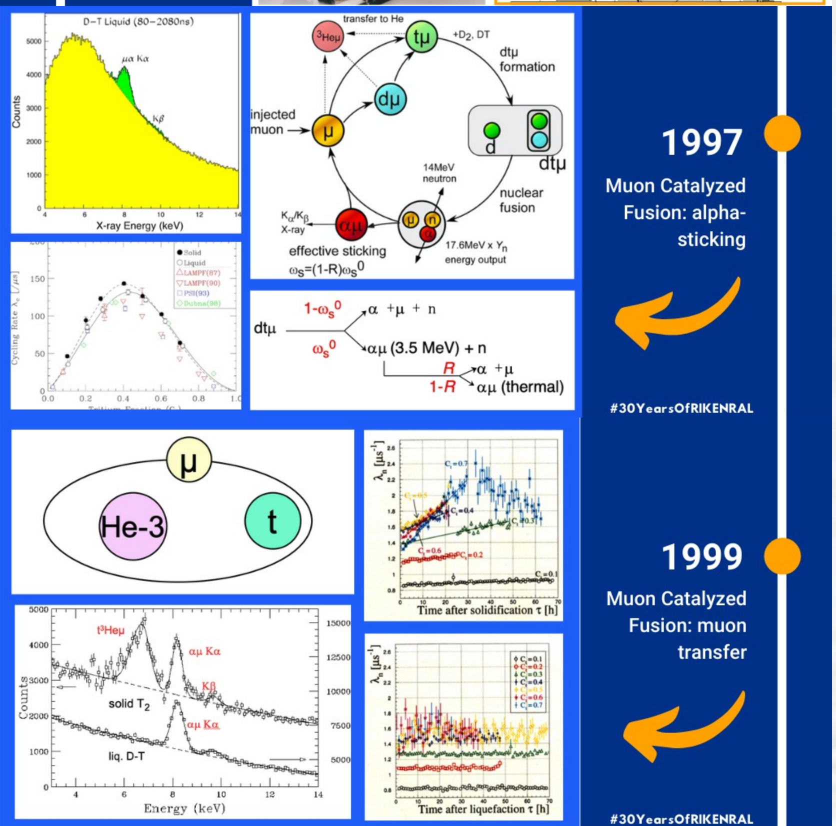
RIKEN-RAL Muon Group

RIKEN
Variable Momentum Muons ~15 – 120 MeV/c
Positive or negative muons
Longitudinal fields up to 0.4 T
Transverse fields up to 600+ G (pulse width limited)
Temperature range 30mK – 500K
Pressure
Elemental Analysis
Ports for long term experiments

ISIS-2 upgrade plans from ~2040: The UK's next-generation neutron and muon source

RIKEN-RAL collaboration

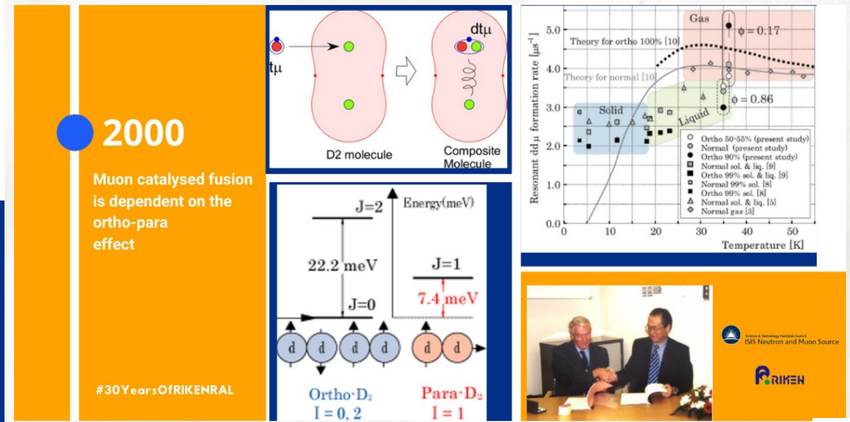




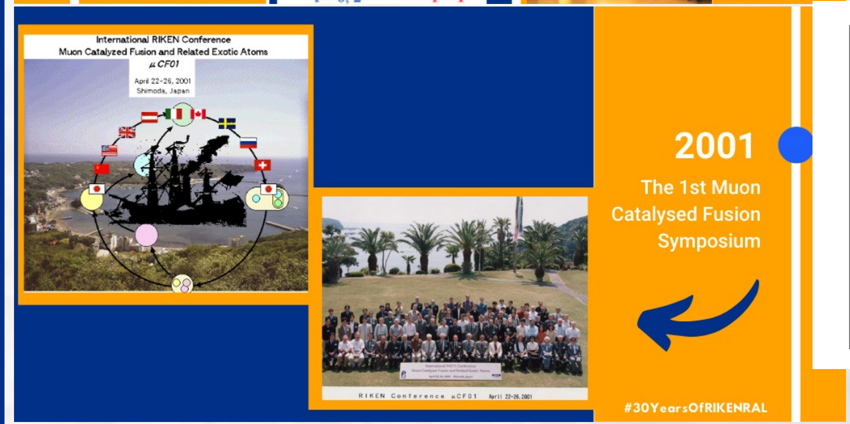
30 years RIKEN at ISIS

Muon beamline was sponsored and funded by Japan at 1990s

In 2018, ownership of the RIKEN-RAL facility passed to ISIS



μCF – was one of key topic on this facility



Summary of d-t μCF experiments

Result:
Neutron yield (max.): 111 /μ⁻ (40% solid) , 100 /μ⁻ (50% liquid)
Cycling rate (max.): 110/μsec (40% solid) , 99/μsec (40-50% liquid)
Sticking probability (ω_s) (averaged):
0.53 +/-0.03 % (liquid), 0.52 +/-0.03 % (solid)
Initial sticking probability (ω_0) : 0.912% (assumed)
Reactivation factor (R): 0.42

Fusion rate in the experiment:
Muon stopping number in the D-T target: 130μ⁻ /spill
Fusion rate: 0.72 x 10⁶ /sec. (about one million d-t fusions / second)

Temperature dependence in D-T solid at 5- 16K:
λ_c : increase by 20% (as increasing temperature)
W: decrease
Y_x/Y_n: nearly constant

RIKEN-RAL facility

μCF facility in RAL was in operation 1996-2006

everything was decommissioned at ~2015-2018

MuFusE Collaboration

Diamond anvil muon catalyzed fusion (MuFusE Collaboration)
PSI BVR25, A. Knaian, K. Lynch et al.

A. Adamczak[o], J.A. Allen[a], A. Antognini[c,m], E. G. Badaracco[d,i], J. Betances[a,n], N.J. Brennan[a], R. Chaney[a], W. Cutler[f,j], J. Davies[e], C. Fagan[p], C. Forrest[e], A P. P. Gandhi[d], V. Glebov[e], A. Golossanov[c,f], D.M. Harrington[a], G. Harris[f], J.T. Hinchen[a], P.A. Holden[a], C. Izzo[d], C. Johnstone[d], J.D. Kalow[a], K. Kem[a], M. Khandaker[a], M. Kiburg[d], I. Kiniti[a,n], A.N. Knaian[a,c,d,f,2], L.E. Knaian[f], E. Koukina[f], K. Lau[a], J. Larson[k], K.R. Lynch[b,d,2], N.A. MacFadden[a,g], A. Mazzacane[d], P.A. McDaniel[a], M. Mundt[a,j], S.O. Newburg[a,f], E. Niner, K. Payne[a], C.C. Petitjean[c], R. Ridgeway[d], A. Sampat[a], C.R. Shmayda[q], W.T. Shmayda[e,l], W. Stadolnik[a,j], I.D. Spool[a], S. Tripathy[b,d], S. Varner[a], D. Zajac[a,j]

Acceleron Fusion, Inc. (Cambridge, USA)
https://www.acceleron.energy/

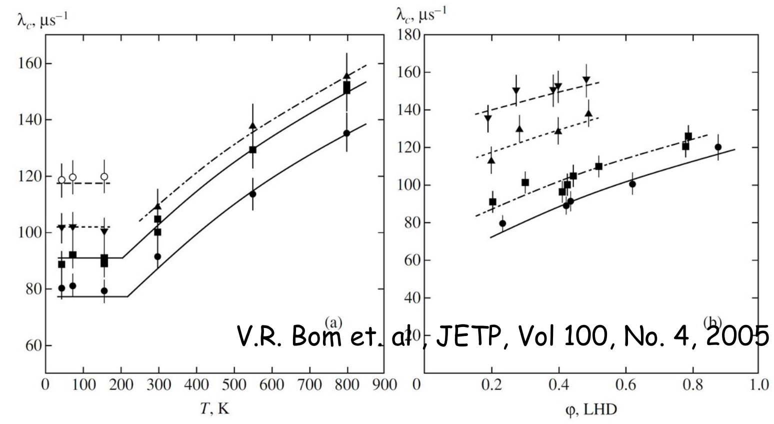
https://spectrum.ieee.org/colder-muon-fusion-energy

24M$ funded by investors at 2024

Acceleron Fusion, Inc. (Cambridge, USA)

Fermilab Workshop on Low Energy Muon Physics and Muonium, Jul 2022
Progress report to the Paul Scherrer Institute beam allocation committee, Feb 2023
PSI BVR25, A. Knaian, K. Lynch et al., Feb 2025

Temperature and Density Increase Fusion Rate

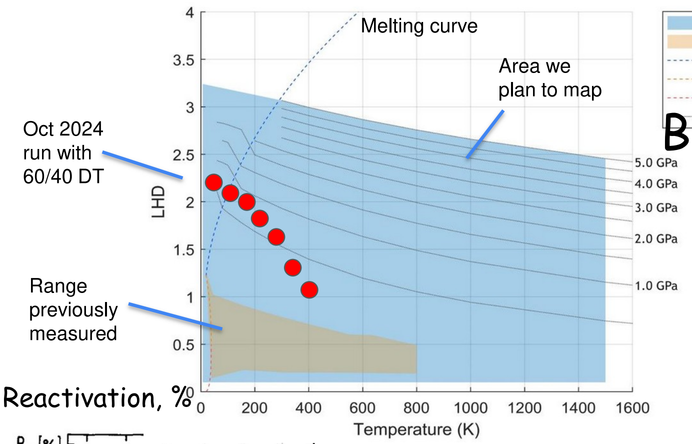


V.R. Bom et. al , JETP, Vol 100, No. 4, 2005

Fig. 12. (a) Normalized cycling rates as a function of temperature for the gaseous D/T mixture at $C_t \approx 33\%$ and different densities φ = 0.88–0.91 (○), 0.62–0.64 (▼), 0.49–0.52 (▲), 0.39–0.45 (■), 0.19–0.24 (●) LHD. (b) Normalized cycling rates as a function of density for the gaseous D/T mixture at $C_t \approx 33\%$ and different temperatures T = 800 K, C_t = 0.34–0.36 (▼); T = 550 K, C_t = 0.33–0.36 (▲); T = 300 K, C_t = 0.31–0.36 (■); T = 158 K, C_t = 0.31 (●). The curves are obtained with optimum parameters.

Diamond Anvil Measurement

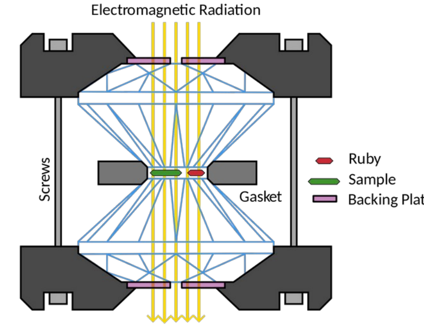
Want to exploit high P and T



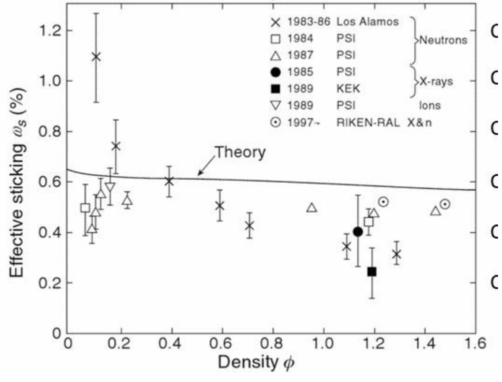
Experiments at piE1, PSI

Next beam time Oct.2025

Basic Experimental Layout



Increasing Density Reduces Sticking



K. Nagamine, 2008

Muon from sticking Reactivation, %

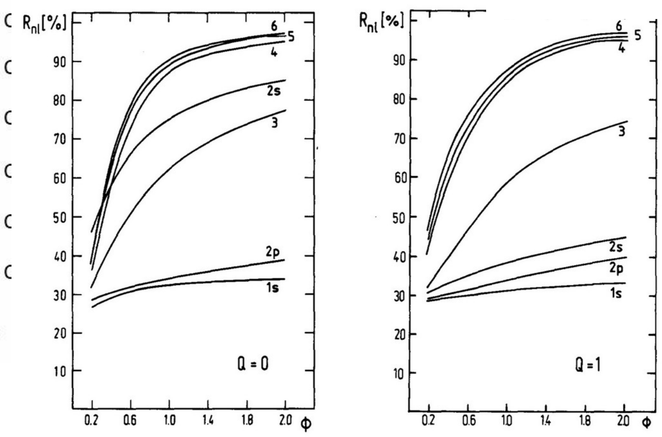
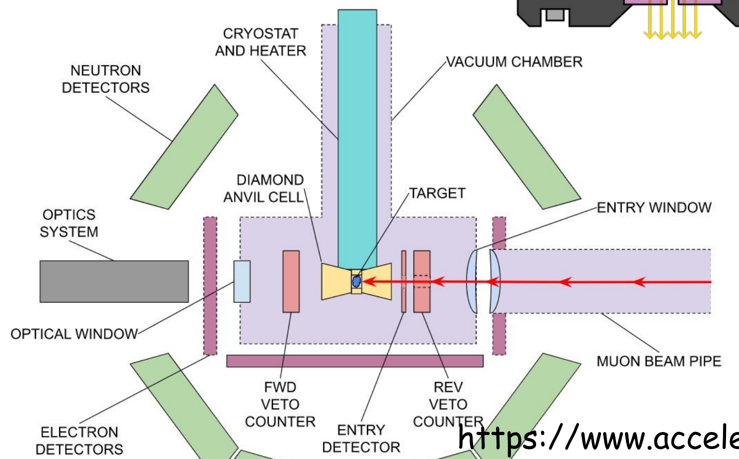


Fig. 2: Reactivation probabilities R_{nl} following on (dtµ) fusion. (a) Q=0: no 2p-2s quenching, (b) Q=1: full 2p-2s quenching.

H. Rafelski, Muon Reactivation in Muon-Catalyzed D-T Fusion



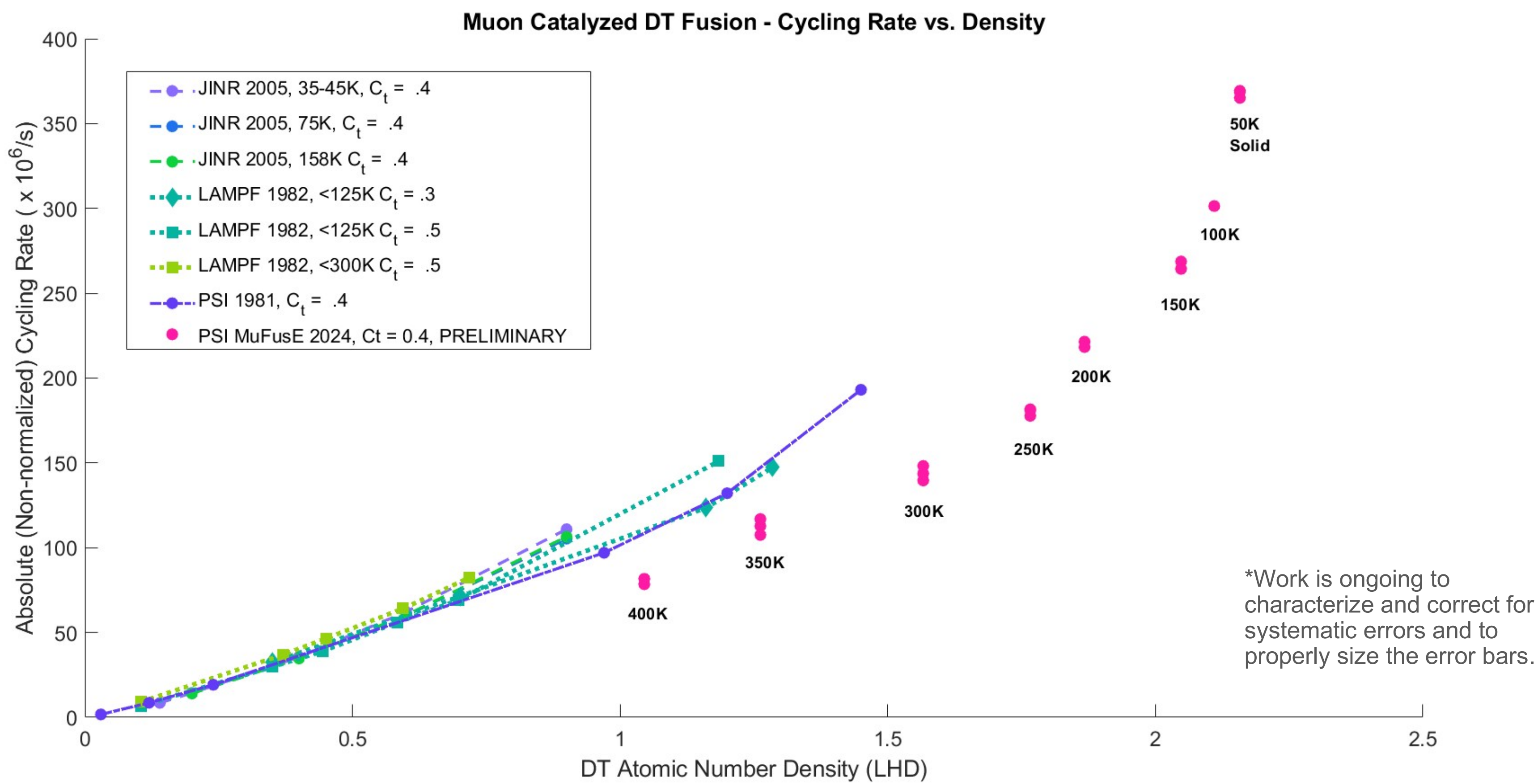
https://www.acceleron.energy/
https://spectrum.ieee.org/colder-muon-fusion-energy
24M$ funded by investors

Results

MuFusE Collaboration

Experiments at piE1, PSI
Next beam time Oct.2025

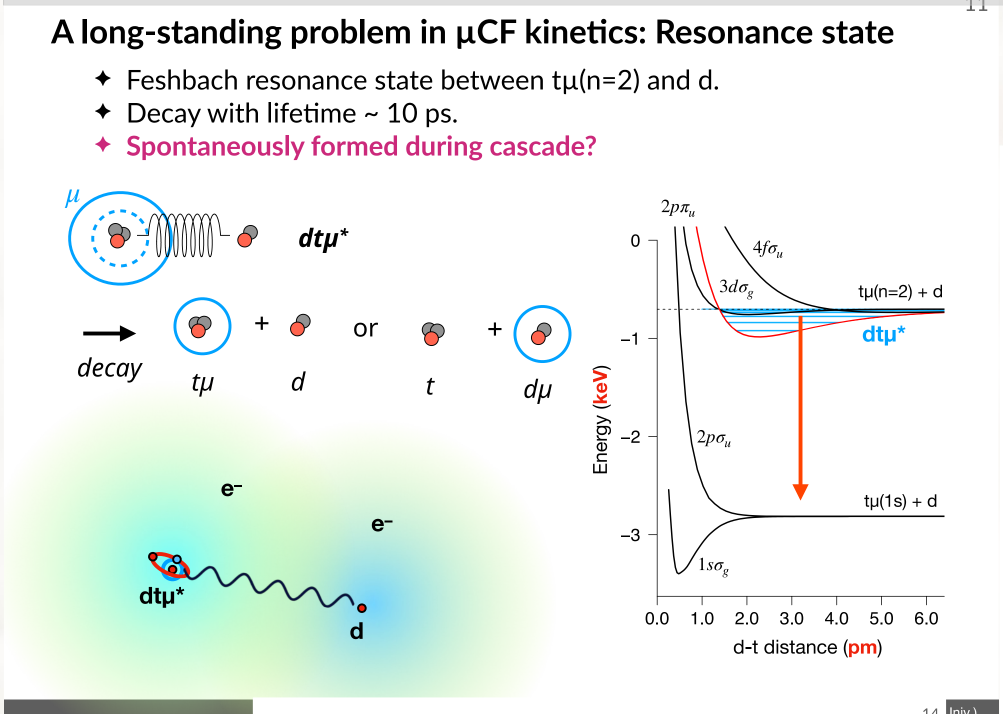
PRELIMINARY data on DT cycling rate to 2.2 LHD (2024)

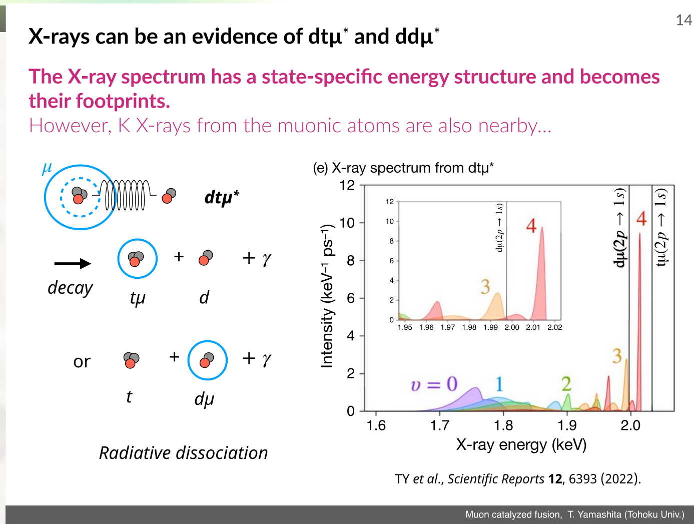


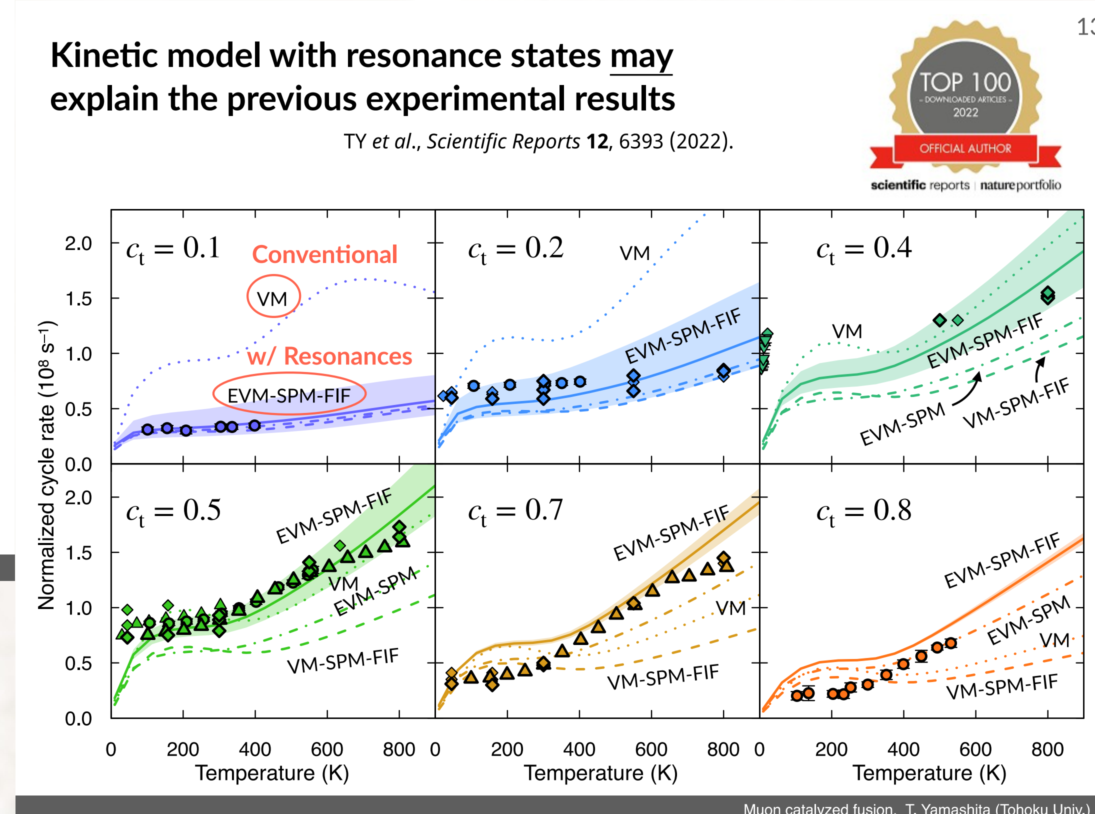
Effect of tμ(n=2) +d resonances on MCF rate

T.Yamashita et al., Scientific Reports 12, 6393 (2022)

Takuma Yamashita, Muon4Future 2025







tμ(n=2) +d can form resonances

Can be studied by looking on K X-rays spectra

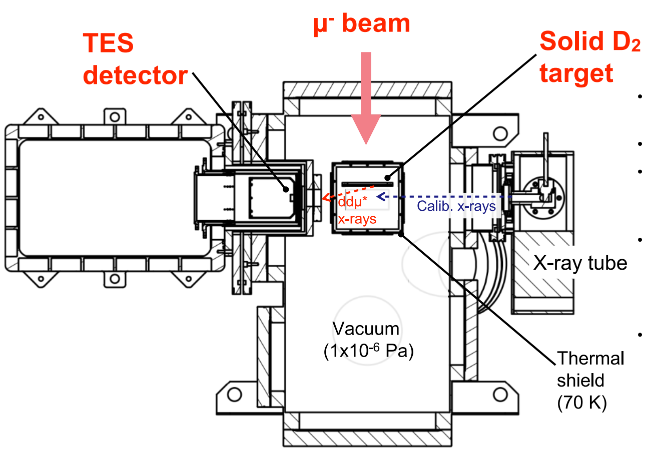
J PARC experiment

studies by looking on K X-rays spectra
using Transiton-edge sensor (TES) for precise X-ray spectrometry

Takuma Yamashita, Muon4Future 2025

Experiment at J-PARC with TES detector & solid D_2 target

Note: We used pure D_2 instead of D_2-T_2 mixture as the first step

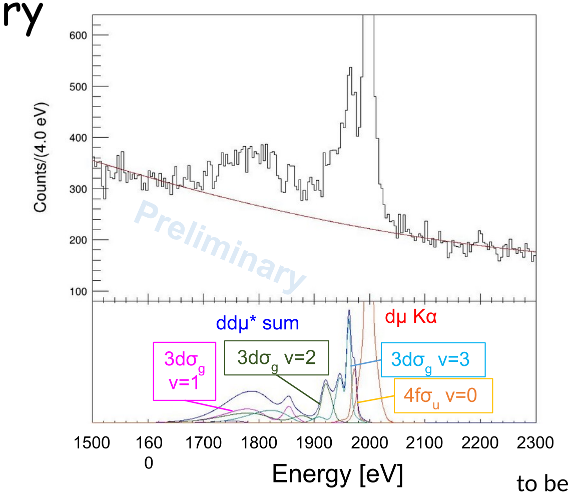


Feb 5 - 11, 2023

- μ^- beam was irradiated to the solid deuterium target.
- ddμ* was produced in the target
- Dissociative X-rays of ddμ* were detected by TES detector
  - Transmittance: ~40%@2 keV
- Calibration X-rays from X-ray tube were measured simultaneously.
- Other detectors
  - Plastic scintillator + PMT (for decay e^-)
  - SDD (for reference)
  - MiniPIX (for proton, scattered μ^-)

Y. Toyama et al., EXA conference (2024).

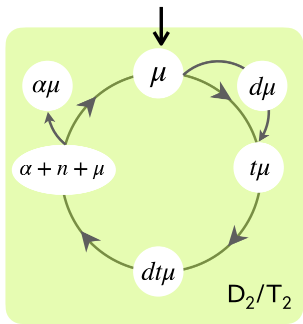
Results of the experiment: Close-up view



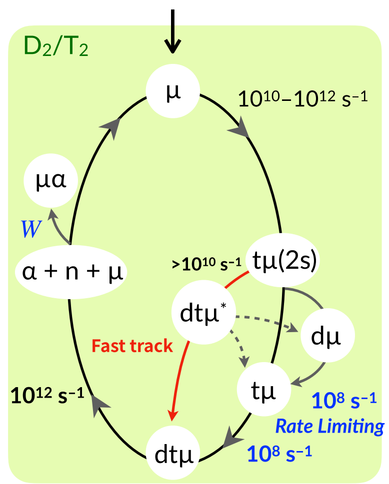
to be submitted

Possible application of RB transition: Fast track

Conventional model



New model w/ resonance-bound path



De-excitation rate of tμ(2s) via dtμ* into dtμ (*if selected*) is faster than ordinary Vesman formation of dtμ from tμ(1s), rate-limiting process.

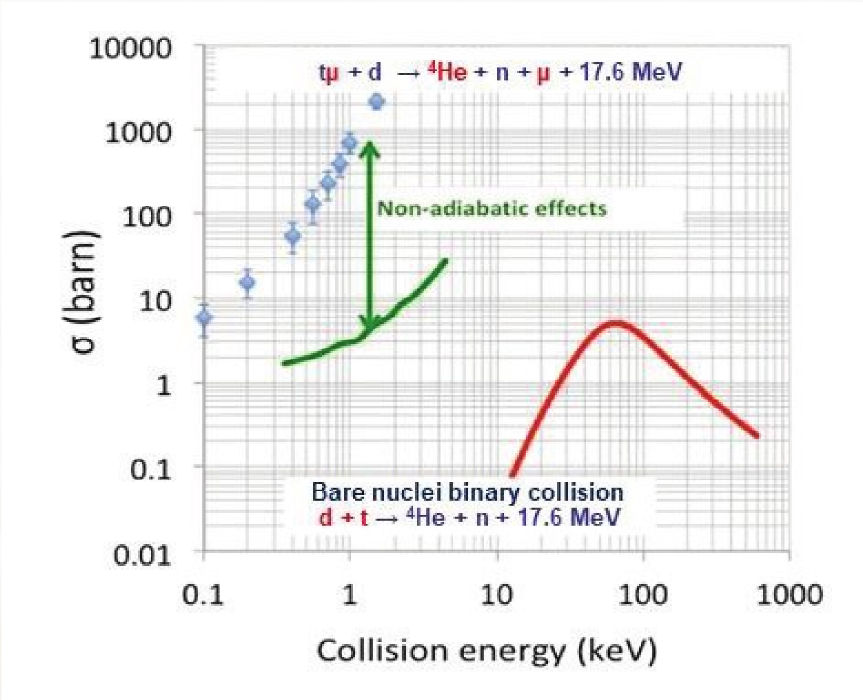
First observation of ddμ* resonance states with a high branching ratio directly to dtμ bound state molecule.

Formation of molecular resonances affects CF rate

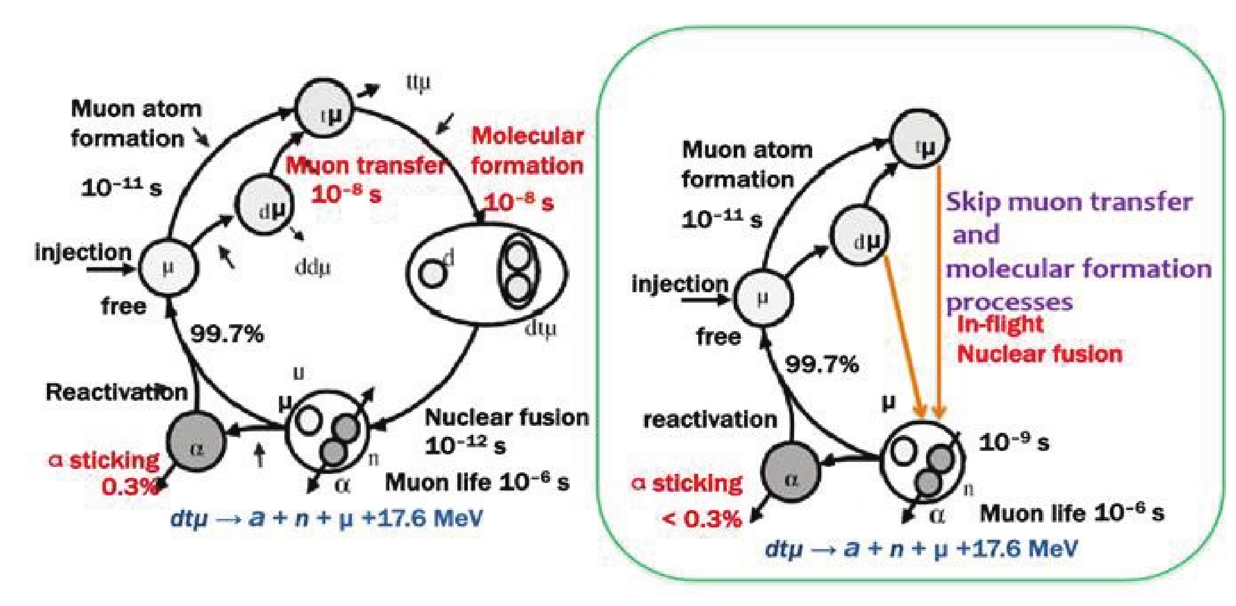
In-flight muon catalyzed fusion (IFMCF)

Atsuo Iiyoshi,
AIP Conf. Proc. 2179, 020010 (2019)

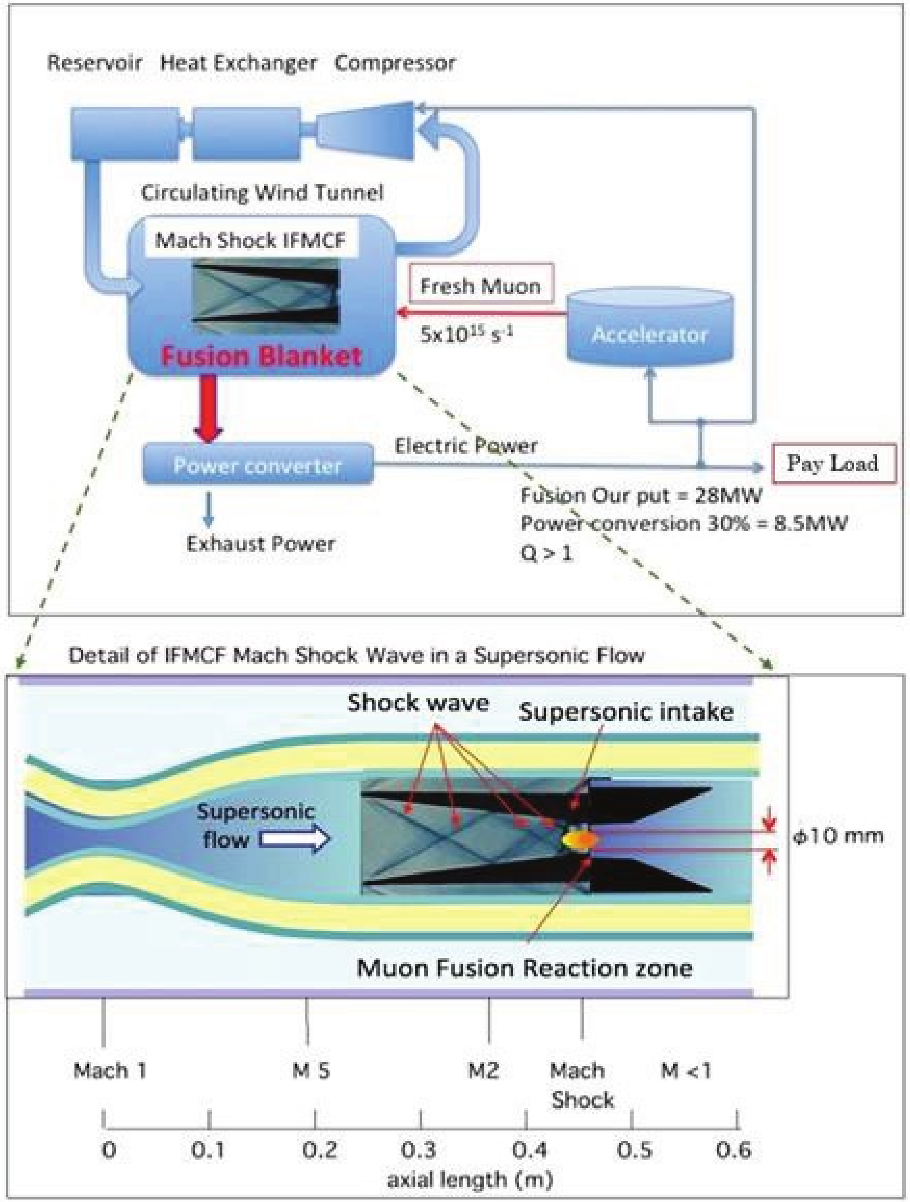
tμ + d → fusion cross section increase with T



Skipping thermal dtμ molecular formation
+ muon regeneration by $(\alpha\mu)^+$ stripping through high-T plasma
→ higher μCF rate ~ 1000 fusion/μ ?



In-flight muon catalyzed fusion (IFMCF)



Atsuo Iiyoshi,
AIP Conf. Proc. 2179, 020010 (2019)

Fresh free **10^{16} muon/s**

x1000 fusions

28 MW fusion output

8.5 MW electricity

What about muons cost?

Most of MCF related papers cites theoretical lowest cost 5 GeV/muon
→ 8MW price for 10^{16} muon/s
assuming 100% efficiency of power conversion
→ needs 300 fusion/muon

M.Jandel, CERN-TH-4810/87, 1987
Needs >700 fusion/muon, but require low density

Muon intensity/precision frontier facilities

μ as a tool for precision measurements

Mu2e: μN → eN

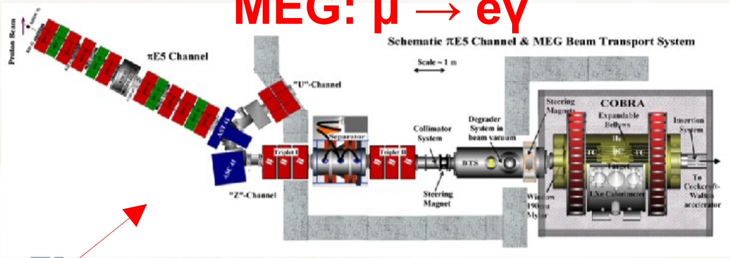
Pulsed rate
5 × 10^{10} μ^{+}/sec

Fermilab

DC rate
2.5 × 10^{8} μ^{+}/sec
HiMB O(10^{10})

PAUL SCHERRER INSTITUT PSI

MEG: μ → eγ



COMET: μN → eN

Pulsed rate
1 × 10^{11} μ^{+}/sec

J-PARC

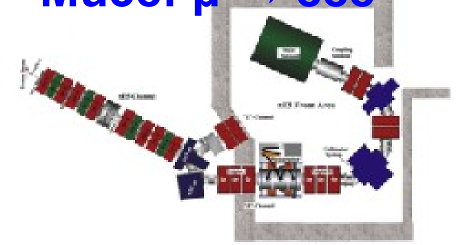
MUSIC
Muon Science Innovative Commission
at RCNP, Osaka University

DC rate
10^{8} μ^{+}/sec

DeeMe: μN → eN

FNAL g-2

Mu3e: μ → eee



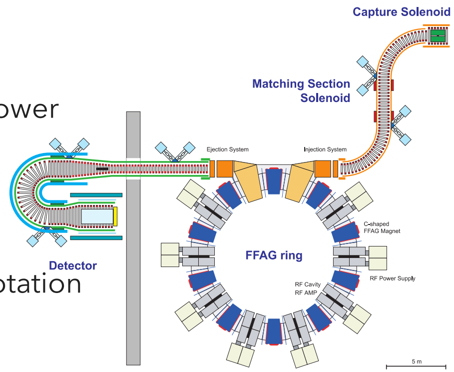
J- PARC g-2

Future Muon facilities

PRISM / PRIME experiments at J-PARC

PRISM specifications (Akira's baseline lattice)

- Intensity :
  - 2×10^{12} muons/sec.
  - for multi-MW proton beam power
- Central Momentum :
  - 68 MeV/c
- Momentum Spread :
  - ±3% (from ±20%) by phase rotation
- Beam Repetition :
  - 100 - 1000 Hz
  - due to repetition of kicker magnets of the muon storage ring.
- Beam Energy Selection :
  - 68 MeV/c ±2%
  - at extraction of the muon storage ring.



Akira Sato, NuFact2023 14

The intensity is planned to be reached mostly by increasing power consumption

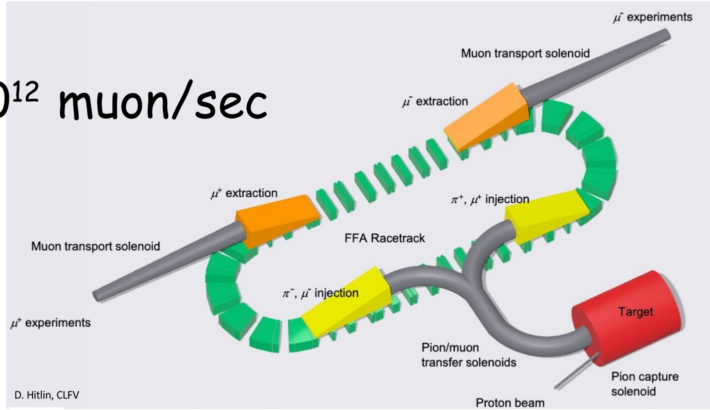
~ 1-10 MW proton driver → 10^{12} - 10^{13} muon/sec

The Advanced Muon Facility at Fermilab

AMF: Cartoon Overview

Muon/anti-muon scenario

~10^{12} muon/sec



- A concept based on the racetrack evolution of PRISM
- Would be designed for the lowest practical muon momentum (30-40 MeV/c)
- The + and – beams are quite diffuse and do not interact, so can co-exist in the ring
- Charge selection in the transfer solenoids is done by displacement
- The yellow and orange boxes (not to scale) represent the kickers and matching sections
- Injection and extraction kickers are rather different
- Injection/extraction is done out of the plane vertically due to beam aspect ratio
  - Can this be done with two beams?

Caltech

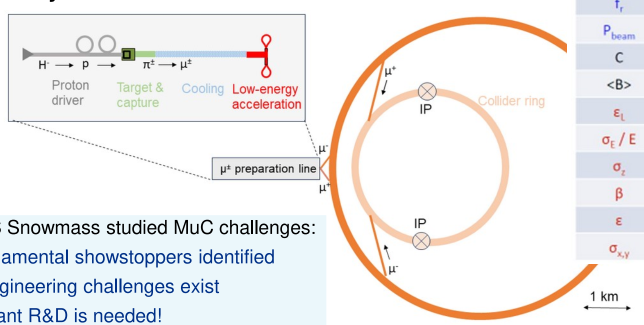
Sophie Middleton, NuFact2024

The Advanced Muon Facility at Fermilab – Sophie Middleton – sophie@fnal.gov 15

Muon Collider

Machine overview

- Goal is to get to **10 TeV center-of-mass energy**
- Two approaches: Staging in **energy** (3 TeV to 10 TeV) or in **luminosity**



IMCC & US Snowmass studied MuC challenges:
- No fundamental showstoppers identified
- BUT engineering challenges exist
- Significant R&D is needed!

CERN-led Muon Collider Collaboration

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Diktys Stratakis, Muons4Future 2025

8 05/26/25 Muons4Future 2025 Fermilab

Mu2e-II vs. Mu2e proton beamlines

Mu2e/Mu2e-II

J. Miller, P5 , 2023

Parameter	Mu2e	Mu2e-II	Comment
Proton source	Slow extraction from DR	PIP-II Linac	
Proton kinetic energy	8 GeV	0.8 GeV	
Beam Power for expt.	8 kW	100 kW	Mu2e-II can be increased
Protons/s	6.25×10^{12}	7.8×10^{14}	
Pulse Cycle Length	1.693 μs	1.693 μs	variable for Mu2e-II
Proton rms emittance	2.7	0.25	mm-mrad, normalized
Proton geometric emittance	0.29	0.16	mm-mrad, unnormalized
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV	
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}	
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}	
Stopped μ per cycle		1.2×10^{5}	
Stopped muons per second	9.9×10^{9}	7.1×10^{10}	

J. Miller, I

MAP Collider Parameters

* as developed by the US MAP

RAST, Vol 10, No. 01, pp. 189-214 (2019)

Parameter	*Units*	*Higgs*	*Top - High Resolution*	*Top - High Luminosity*	*Multi-TeV*		
CoM Energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	7,000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring Depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition Rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. Trans. Emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4	4	4	4	4	1.6
Wall Plug Power	MW	200	203	203	216	230	270

*Accounts for off-site neutrino radiation

Accelerator design meeting, 2021, Shiltsev

Muon cost

Modern Mu2e/COMET muon production facilities

17 MeV x 100 fusion/muon x **10^{11} muon/sec** → **30 W**

Future Muon Collider

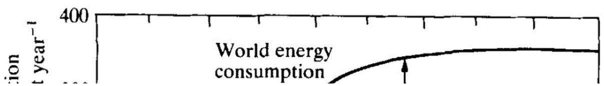
10^{13} muon/sec → **3 kW**

At price of ~ 10 MW proton driver (another x10 for wall plug cost)

μCF needs to have 3-4 order magnitude more intensive muons source
at 3-4 order cheaper price

Would be huge breakthrough for particle physics

Muon cost is issue



Prospects

MuCF program at RIKEN-RAL has observed many interesting process.
We have to close it in a safe state.

The reduction of muon-to-alpha still seems difficult,
giving the limit on number of fusions.
If an efficient way of muon production is considered,
the balance could change the situation.

This conclusion is valid for all the alternative methods of energy production: thermonuclear, laser, inertial etc., and muon catalysed fusion is no exception in this respect. We only hope that in future it will have a worthy place among them.

If only one of the alternative breeding methods turns out to be successful, the Earth's supply of ^{238}U is enough for mankind to be free of energy problems for

phenomenon ought to be continued. (Among recent work in this direction one could mention the theoretical studies of μ-catalysis in a dense low temperature plasma (Menshikov *et al.* 1988, 1989)).

In the past ten years most attention has been paid to studying the processes of the μ-catalysis phenomenon itself: calculations of mesic molecular energy levels and of various mesic atomic and mesic molecular processes, in particular, the detailed description of ddμ and dtμ molecule resonant formation. Certainly this work should be continued and one should try to determine the conditions under which the probability ω_s of muon sticking to helium can be decreased and the μ-catalysis cycle rate λ_c (i.e. the number of μ-catalysis cycles) increased.

But from the point of view of practical applications, the least studied and the most important physical problem now is to find the optimal conditions for the production of π-mesons and, as far as it is possible, to decrease the energy expenditure for their production. It is also necessary to obtain the same characteristics for the capture of 14·1 MeV neutrons in the different blankets.

It is important also to obtain reliable experimental information on electronuclear breeding (the number of fissions, the plutonium yield, etc.) over a wide range of accelerator beam energies.

And, finally, the development of various types of high current deuteron accelerators with energy $\geqslant$ 1 GeV nucleon^{-1} and $I \geqslant 100$ mA should be intensified to estimate the possibility of their construction and the necessary investment.

Acknowledgements

I am sincerely indebted to Sir Charles Frank O.B.E., F.R.S. who has initiated the writing of this review and to Professor J. S. Dugdale for his encouraging support. I am also grateful to D. Bakalov, L. N. Bogdanova,

Outlook

Physics of μCF itself is very interesting

improving theoretical tools/descriptions of multi body process and etc should be useful in others fields (astrophysics, plasma physics, thermonuclear synthesis)

Future energy source

low-T fusion, No plasma confinement;

150 fusions/muon has been achieved so far

didn't change much from first resonance production discovery

is it possible to reach 300-1000 fusions/muon?

Needs x10^4 more powerful and 1/10^4 cheaper muon source

maybe something in between of usual thermo fusion and μCF can give some profit

Mono-energetic neutron source

Material analysis

Transmutation of long lived fission nuclear waste,

Nuclear fuel breeding (n^{fast} + ^{238}U -> ^{239}Pu used in power plants)

Ultra-slow muons ~10 keV

as cooled source for a muon accelerator