SUMMARY TALK

Leonid I. Ponomarev

RRC “Kurchatov Institute” and MUCATEX

73 participants
54 talks
27 laboratories
14 states
1937 - muon discovery
1947 - prediction of $\mu$ – catalysis
1957 - observation of $\mu$ – catalysis
1967 - discovery of $d\mu d$ – resonance formation
1977 - prediction and observation of $d\mu t$ – resonance formation
1987 - $\mu CF$ – conference in Gatchina, where $\mu CF$ – community was finally established.

Today the essential part of the $\mu CF$ – community is involved in the different activities, but it is alive and still remembers those exciting time when we were much more younger.
\(\mu CF\) – meetings:

- 1984 – Jackson Hall, Wyoming, USA
- 1986 – Tokyo, Japan
- 1987 – Gatchina, Russia
- 1988 – Sanibel Island, Florida, USA
- 1989 – Oxford, UK
- 1990 – Vienna, Austria
- 1992 – Uppsala, Sweden
- 1995 – Dubna, Russia
- 1998 – Ascona, Switzerland
- 2001 – Shimoda, Japan
- 2004 – Vienna, Austria
- 2007 – Dubna, Russia
RUSSIA
KIAE Moscow
PNPI Gatchina
Moscow Univ.
St.-Petersburg Univ.
JINR Dubna
ITEP Moscow
INR Troitsk
IHEP Protvino
IATE Obninsk
RFNC Arzamas

USA
Berkeley
Los Alamos
BNL
BYU
William&Mary
California St. Univ.
Delaware Univ.
Florida Univ.

UK
RAL
Nottingham Univ.

JAPAN
RIKEN
KEK
Tokyo Univ.
Kushu Univ.

SWITZERLAND
PSI
Fribourg Univ.
Neuchatel Univ.

ITALY
INFN & ENEA Bologna

GERMANY
TUM Munich

CANADA
TRIUMF Vancouver

AUSTRIA
IMEP Vienna

SWEDEN
Uppsala Univ.

POLAND
INP Krakow

BULGARIA
INRNE Sofia

BELGIUM
Delft Tech. Univ.
J-PARC Facility

Joint Project between KEK and JAEA

Nuclear Transmutation

Materials and Life Science Experimental Facility

Hadron Beam Facility

Neutrino to Kamiokande

J-PARC = Japan Proton Accelerator Research Complex

3 GeV Synchrotron (25 Hz, 1 MW)

50 GeV Synchrotron (0.75 MW)

Linac (330 m)
Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton’s Pseudoscalar Coupling $g_P$


(MuCap Collaboration)

1 Petersburg Nuclear Physics Institute, Gatchina 188350, Russia
2 University of California, Berkeley, and LBNL, Berkeley, CA 94720, USA
3 University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
4 Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium
5 Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
6 University of Kentucky, Lexington, KY 40506, USA
7 Boston University, Boston, MA 02215, USA

(Dated: April 10, 2007)

$\Lambda_S^{\text{MuCap}} = 725.0 \pm 13.7_{\text{stat}} \pm 10.7_{\text{sys}} \text{s}^{-1}$

Average of HBChPT calculations of $\Lambda_S$:

$\frac{(687.4 \text{ s}^{-1} + 695 \text{ s}^{-1})}{2} = 691.2 \text{ s}^{-1}$

Apply new rad. correction (2.8%):

$(1 + 0.028)691.2 \text{ s}^{-1} = 710.6 \text{ s}^{-1}$

Further sub percent theory required

$\Lambda_S^{\text{theory}} = 710.6 \text{ s}^{-1}$

$g_P = 7.3 \pm 1.1$

(MuCap 2007)
Coulomb de-excitation

\[(p\mu)_n + H \rightarrow (p\mu)_{n-1} + H\]

- 2005
  Korenman, Pomerantsev, Popov
- 2006
  Kravtsov and Mikhailov
- 2007
  Present work

\[\lambda_{n, n-1}, 10^{11} s^{-1}\]

\[E_{cm}, \text{eV}\]
“A young woman is attractive by her beauty, a grown lady is interesting by her children.”

R. Feynman

μCF beauty is well known now:

This is a unique phenomenon which allows to regulate the yield of nuclear synthesis by variations of macroscopic parameters – temperature, density, hydrogen isotope concentration, and it is already included in some textbooks.
μCF application in Fundamental Physics and Nuclear Technology

- Atomic & Molecular Physics
- Weak Interaction Physics
- Tritium Technology
- Neutron Source
- High Power Accelerator
- Nuclear Breeding
- RW Transmutation
- Nuclear Physics
- QED
µCF-applications in fundamental physics

• effective numerical codes;
• weak interaction physics;
• nuclear physics and astrophysics;
• \( \bar{p} \)-physics.
Effective numerical codes and \(\bar{p}\)-physics

The accuracy of calculations achieved in the quantum three-body problem with Coulomb interaction is \(10^{-8} - 10^{-9}\). This is 1000 times more than the precision of the world constant. It allows to calculate transition energies in the \(\bar{p}\mathrm{He}^+\) system with the spectroscopic precision.
Nuclear physics and astrophysics

Measurements of nuclear fusion rates

- “at rest”;
- from a definite initial state.
Measurements of branching ratio $R$ as a function of temperature in $D_2$ and HD.

$R = \frac{dd \rightarrow n + ^3He}{dd \rightarrow p + t}$

Branching ratio

$R_{J=1} = 1.450(11)$

- Resonant formation in $J=1$ state only

$R_{J=0} = 0.90(12)$

- Nonresonant formation in $J=0$ state only

Measurements of branching ratio $R$ as a function of temperature in $D_2$ and HD.
Reaction $dd\mu \rightarrow ^4\text{He} + \mu + \gamma$ was never studied.

Cross section of $dd$ radiative capture is small, relative yield with respect to main fusion channels is $\Gamma_\gamma/\Gamma_{p,n} \approx 10^{-7}$.

Cross section energy and angular dependencies are extremely sensitive to $^4\text{He}$ structure.

Low–energy data are needed for astrophysical calculations and plasma diagnostics.

Indications to a $p$-wave transition forbidden by isotopic invariance of nuclear forces were obtained from in-flight measurements.

We use properties of $dd\mu$ molecule resonance formation to study this reaction in the $p$-wave to pin down a forbidden transition.

S-factor for $d(d,\gamma)^4\text{He}$
TRITON

Gas mixture preparation facility

Targets
- SDT 5.5 – 60 K
- LTT ~22K
- HPTT 20-800K up to 1600 bar 2 modifications
- HPDT 77-800K up to 1500 bar

4 π detector system
Readout system based on FADS
New data evaluation method
14 MeV Intense Neutron Source Based On Muon Catalyzed Fusion

1 - deutron beam channel; 2 - primary target; 3 - converter; 4 - superconductive solenoid; 5 - magnetic mirrors; 6 - synthesizer; 7 - specimens area; 8 - systems of tritium fuel loop; 9 - insert of synthesizer; 10 - shielding; 11 - magnetic screen

Intensity $I \approx 10^{17}$ n/s;
Flux $\Phi \approx 10^{14}$ n/s·cm²
Hot Fusion
\[ d + t \rightarrow ^4\text{He} + n \]

\[ \mu^- + (D/T) \rightarrow d\mu t \rightarrow 4\text{He} + n + \mu^- \]

\[ n \ (14.1 \text{ MeV}) + ^4\text{He} \ (3.5 \text{ MeV}) \]

Plasma
- \( \sim 10^8 \text{ K} \)
- \( \sim 10^{14} \text{ cm}^{-3} \)

\[ \mu^- - \text{molecule} \]
- \( < 10^3 \text{ K} \)
- \( \sim 10^{22} \text{ cm}^{-3} \)

state

temperature
density
Fission
\[ n + U \rightarrow \text{fragments} + 200 \text{ MeV} \]

Fusion
\[ t + d \rightarrow ^4\text{He} + n + 17.6 \text{ MeV} = ^4\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \]

Tritium Production
\[ n + ^6\text{Li} \rightarrow t + ^4\text{He} \]

One neutron is necessary to produce one tritium nucleus. 14 MeV neutron takes \( \sim 200 \text{ MeV} \), but it is very productive:
in the hot fusion reactor it can produce \( t + 1 \) fission +1.6 \(^{239}\text{Pu}\), i.e. \( \sim 700 \text{ MeV} \);
in the \( \mu \text{CF}-\text{breeder} \) \( n (14.1 \text{ MeV}) + U + ^6\text{Li} \rightarrow t + 1 \) fission + 3 \(^{239}\text{Pu}\) = \( t + 1000 \text{ MeV} \).

SUMMARY:

\[
\begin{align*}
\text{Fusion} & : 17.6 \text{ MeV;} \\
\text{Fission} & : 200 \text{ MeV;} \\
\text{Hot fusion breeder} & : 700 \text{ MeV;} \\
\text{\( \mu \text{CF} \)-breeder} & : 1000 \text{ MeV;} \\
\text{Tritium production} & : 200 \text{ MeV.}
\end{align*}
\]
### Main Characteristics of μCF-cycles.

<table>
<thead>
<tr>
<th>Цикл</th>
<th>Реакции</th>
<th>$\lambda_m$, c(^{-1})</th>
<th>$\lambda_f$, c(^{-1})</th>
<th>$\omega_s$</th>
<th>$\lambda_{ab}$, c(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pd</strong></td>
<td>$p\mu \xrightarrow{\lambda_{pd}} d\mu \xrightarrow{\lambda_{pd\mu}} p\mu \xrightarrow{\lambda_f} \mu^3\text{He} + \mu^-$</td>
<td>5.8 \times 10^6</td>
<td>2.6 \times 10^5</td>
<td>0.99</td>
<td>1.7 \times 10^{10}</td>
</tr>
<tr>
<td><strong>pt</strong></td>
<td>$p\mu \xrightarrow{\lambda_{pt}} t\mu \xrightarrow{\lambda_{pt\mu}} p\mu \xrightarrow{\lambda_f} \mu^4\text{He} + \gamma$</td>
<td>6.8 \times 10^6</td>
<td>0.7 \times 10^5</td>
<td>0.94</td>
<td>0.7 \times 10^{10}</td>
</tr>
<tr>
<td><strong>dd</strong></td>
<td>$d\mu \xrightarrow{\lambda_{dd\mu}} dd\mu \xrightarrow{\lambda_f} \mu^3\text{He} + n$</td>
<td>$\sim$ 3 \times 10^6</td>
<td>4.3 \times 10^8</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td><strong>dt</strong></td>
<td>$d\mu \xrightarrow{\lambda_{dt\mu}} t\mu \xrightarrow{\lambda_{dt\mu}} dt\mu \xrightarrow{\lambda_f} \mu^4\text{He} + n$</td>
<td>$\sim$ 3 \times 10^8</td>
<td>1.2 \times 10^{10}</td>
<td>0.0087</td>
<td>2.8 \times 10^8</td>
</tr>
<tr>
<td><strong>tt</strong></td>
<td>$t\mu \xrightarrow{\lambda_{tt\mu}} tt\mu \xrightarrow{\lambda_f} \mu^4\text{He} + 2n$</td>
<td>3 \times 10^6</td>
<td>1.5 \times 10^7</td>
<td>0.14</td>
<td>-</td>
</tr>
</tbody>
</table>

*) $\lambda_0 = 0.46 \times 10^6$ c\(^{-1}\) – is the muon decay rate ($\mu \rightarrow e + \nu_\mu + \bar{\nu}_e$);
$\lambda_m = \lambda_{pd\mu}, \lambda_{dd\mu}$ – are the mesic molecules formation rates ($\lambda_{dd\mu}$ and $\lambda_{dt\mu}$ depend on temperature);
$\lambda_f$ – is the nuclear synthesis rate;
$\omega_s$ – is the sticking probability;
$\lambda_{ab}$ – isotope exchange rate $a\mu + b \rightarrow b\mu + a$;
All data are reduced to 300 K and density of liquid hydrogen $n_0 = 4.25 \times 10^{22}$ cm\(^{-3}\).
Muon decay:
\[ \mu \rightarrow e + \nu_\mu + \nu_e \]

Number of cycles:
\[ Y_c = \frac{\lambda_c}{\lambda_0 + \omega_s \cdot \lambda_c} \]
## Relativistic and other corrections (meV) to the nonrelativistic energies $\varepsilon_{11}^{NR}$ of muonic molecular ions

<table>
<thead>
<tr>
<th></th>
<th>1992</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$dd\mu$</td>
<td>$dt\mu$</td>
</tr>
<tr>
<td>Nonrelativistic energy</td>
<td>-1974.82</td>
<td>-660.17</td>
</tr>
<tr>
<td>Vacuum polarization</td>
<td>8.7</td>
<td>16.6</td>
</tr>
<tr>
<td>Electromagnetic structure of nuclei</td>
<td>-1.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Relativistic shift</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Finite size corrections ($Ke$)</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Nuclear polarization</td>
<td>0.0</td>
<td>-1.7</td>
</tr>
<tr>
<td>Total shift</td>
<td>9.6</td>
<td>28.4</td>
</tr>
<tr>
<td>Total energy</td>
<td>-1965.3</td>
<td>-631.8</td>
</tr>
</tbody>
</table>

*The accuracy 0.1 meV is equivalent $\Delta T \sim 1K$.)*


**Binding energy of the weakly bound\( d\bar{t}\mu(11) \)**

molecular ion

<table>
<thead>
<tr>
<th></th>
<th>year</th>
<th>(N)</th>
<th>(E_{nr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinitsky et al</td>
<td>1980</td>
<td>adiab</td>
<td>0.64(5)</td>
</tr>
<tr>
<td>Goecheva et al</td>
<td>1984</td>
<td>adiab</td>
<td>0.656</td>
</tr>
<tr>
<td>Frolov, Efros</td>
<td>1985</td>
<td>400</td>
<td>0.60719</td>
</tr>
<tr>
<td>Hu</td>
<td>1986</td>
<td>500</td>
<td>0.628</td>
</tr>
<tr>
<td>Korobov</td>
<td>1986</td>
<td>1286</td>
<td>0.65889</td>
</tr>
<tr>
<td>Korobov</td>
<td>1987</td>
<td>2084</td>
<td>0.65968</td>
</tr>
<tr>
<td>Szalewicz</td>
<td>1987</td>
<td>3063</td>
<td>0.66001</td>
</tr>
<tr>
<td>Kamimura</td>
<td>1988</td>
<td>2662</td>
<td>0.660104</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.660264*</td>
</tr>
<tr>
<td>Haywood, Monkhorst, Alexander</td>
<td>1991</td>
<td>2600</td>
<td>0.660178</td>
</tr>
<tr>
<td>Frolov</td>
<td>1994</td>
<td>1900</td>
<td>0.660332*</td>
</tr>
<tr>
<td>Korobov</td>
<td>2000</td>
<td>2000</td>
<td>0.66017864</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.66033840*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.66033550**</td>
</tr>
</tbody>
</table>

* calculated with CODATA-86 recommended values;
** calculated with CODATA-98 recommended values.
**ddµ resonant formation rates**

\[
(d\mu)_F + D_2 \rightarrow [(dd\mu)\text{dee}]
\]

**FIT PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theory</th>
<th>Fit to Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-\varepsilon_{11} (\text{eV}))</td>
<td>1.9648</td>
<td>1.9626(3)</td>
</tr>
<tr>
<td>(\lambda_{\text{fus}} (10^6 \text{ s}^{-1}))</td>
<td>460</td>
<td>407(20)</td>
</tr>
</tbody>
</table>

(PSI-PNPI-IMEP-LBNL-TUM-RRC KI – collaboration)
\( \mu \)-molecule nonrelativistic binding energies \( \varepsilon_{Jv} \), eV of the states \((Jv)\)*

<table>
<thead>
<tr>
<th>Molecule ((Jv))</th>
<th>(00)</th>
<th>(01)</th>
<th>(10)</th>
<th>(11)</th>
<th>(20)</th>
<th>(30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \mu \mu )</td>
<td>253.152</td>
<td>-</td>
<td>107.256</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \mu \mu \nu )</td>
<td>221.549</td>
<td>-</td>
<td>97.498</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \mu \nu \nu )</td>
<td>213.840</td>
<td>-</td>
<td>99.127</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \nu \nu \nu )</td>
<td>325.074</td>
<td>35.844</td>
<td>266.682</td>
<td>1.975</td>
<td>86.434</td>
<td>-</td>
</tr>
<tr>
<td>( \nu \nu \mu )</td>
<td>319.140</td>
<td>34.834</td>
<td>232.472</td>
<td>0.660</td>
<td>102.643</td>
<td>-</td>
</tr>
<tr>
<td>( \nu \mu \mu )</td>
<td>362.910</td>
<td>83.771</td>
<td>289.142</td>
<td>45.206</td>
<td>172.526</td>
<td>48.70</td>
</tr>
</tbody>
</table>

* The total binding energies of the loosely bound states \((J=\nu=1)\) of muonic molecules \( d \mu d \) and \( d \mu \nu \), taking into account all the relativistic and other corrections are equal \( \varepsilon_{11}(dd\mu) = 1.965 \) eV and \( \varepsilon_{11}(d\mu\nu) = 0.631 \) eV.
The main characteristics of $\mu$CF-processes*

<table>
<thead>
<tr>
<th>Rates</th>
<th>Numerical value, $\lambda,10^9 \cdot s^{-1}$ at $\varepsilon = 0.04\text{eV}$</th>
<th>Reaction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_\mu$</td>
<td>$\sim 10^9$</td>
<td>$\mu^- + H_2 \rightarrow p\mu + H + \gamma$</td>
<td>Collision energy dependent:</td>
</tr>
<tr>
<td>$\lambda_{\mu d}$</td>
<td>$2.5 \cdot 10^2$</td>
<td>$p\mu + d \rightarrow d\mu + p$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu t}$</td>
<td>$7.0 \cdot 10^4$</td>
<td>$p\mu + t \rightarrow d\mu + p$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d}$</td>
<td>$2.5 \cdot 10^2$</td>
<td>$d\mu + t \rightarrow d\mu + d$</td>
<td>$\mu \gtrsim 0.1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_\mu$</td>
<td>$1.7 \cdot 10^4$</td>
<td>$(\mu p)<em>{\ell=1} + p \rightarrow (\mu p)</em>{\ell=1} + p$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_\mu$</td>
<td>$37$</td>
<td>$(\mu p)<em>{\ell=1} + d \rightarrow (\mu p)</em>{\ell=1} + d$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_\mu$</td>
<td>$1.2 \cdot 10^3$</td>
<td>$(\mu p)<em>{\ell=1} + l \rightarrow (\mu p)</em>{\ell=1} + l$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$1.8$</td>
<td>$p\mu + H_2 \rightarrow \left[(p\mu)_{\ell=1}p\mu\right] + \gamma$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$6.4$</td>
<td>$d\mu + H_2 \rightarrow \left[(d\mu)_{\ell=1}p\mu\right] + \gamma$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$2.6$</td>
<td>$t\mu + H_2 \rightarrow \left[(t\mu)_{\ell=1}p\mu\right] + \gamma$</td>
<td>$\mu \gtrsim 1\text{eV}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$1.8 \cdot 10^2$</td>
<td>$d\mu + D_2 \rightarrow \left[(d\mu)_{\ell=1}d\mu\right] + \gamma$</td>
<td>Temperature and energy dependent</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$5.6 \cdot 10^2$</td>
<td>$t\mu + D_2 \rightarrow \left[(t\mu)_{\ell=1}d\mu\right] + \gamma$</td>
<td>Temperature and energy dependent</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$6.4$</td>
<td>$d\mu + DT \rightarrow \left[(d\mu)_{\ell=1}DT\right] + \gamma$</td>
<td>Temperature and energy dependent</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$2.7$</td>
<td>$t\mu + HD \rightarrow \left[(t\mu)_{\ell=1}DT\right] + \gamma$</td>
<td>Temperature and energy dependent</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$3.0 \cdot 10^2$</td>
<td>$t\mu + D_2 \rightarrow \left[(t\mu)_{\ell=1}d\mu\right] + \gamma$</td>
<td>Temperature and energy dependent</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$0.26$</td>
<td>$p\mu d \rightarrow \mu^3He + \gamma$</td>
<td>Branching ratio of mirror channels</td>
</tr>
<tr>
<td>$\omega_{\mu d\mu}$</td>
<td>$0.86$</td>
<td>$p\mu d \rightarrow \mu^3He + \gamma$</td>
<td>$\beta = \frac{\mu^3He + \gamma}{p\mu d} = 1.40$ at $T &gt; 150\text{K}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$0.07$</td>
<td>$p\mu d \rightarrow \mu^4He + \gamma$</td>
<td>The effective striking probability $\omega_{\mu d\mu} = \frac{4}{\bar{\gamma}}\omega_{\mu d\mu} = 0.078$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$0.94$</td>
<td>$p\mu d \rightarrow \mu^4He + \gamma$</td>
<td>$\beta = \frac{\mu^4He + \gamma}{p\mu d} = 1.40$ at $T &gt; 150\text{K}$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$1.32$</td>
<td>$d\mu d \rightarrow \mu^3He + n + n$</td>
<td>The effective striking probability $\omega_{\mu d\mu} = \frac{4}{\bar{\gamma}}\omega_{\mu d\mu} = 0.078$</td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$1.46 \cdot 10^{-2}$</td>
<td>$d\mu t \rightarrow \mu^3He + n + n$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{\mu d\mu}$</td>
<td>$0.12$</td>
<td>$t\mu t \rightarrow \mu^3He + n + n$</td>
<td></td>
</tr>
<tr>
<td>$R_{dd}$</td>
<td>$0.05$</td>
<td>$\mu^3He + d \rightarrow \frac{3}{2}\mu^3He + d + p$</td>
<td>at liquid hydrogen density</td>
</tr>
<tr>
<td>$R_{dt}$</td>
<td>$0.3$</td>
<td>$\mu^4He + d \rightarrow \frac{4}{2}\mu^4He + d + p$</td>
<td></td>
</tr>
</tbody>
</table>

* All the rates are normalized to the liquid hydrogen density $\varphi_0 = 4.25 \cdot 10^{22} \text{cm}^{-3}$
Figure 5: Scheme of $\mu$CF processes in $H/D/T$ mixtures.
10\(^{-7}\) of muonic Rydberg energy

**Results of the fit to \(\lambda_{1/2}\) and \(\lambda_{3/2}\) and theoretical values.**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Fit</th>
<th>Calculation</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon_{11}) (meV)</td>
<td>(-1966.1(2))</td>
<td>(-1966.2) (^{*})</td>
<td>[34]</td>
</tr>
<tr>
<td>(\lambda_1) ((\mu s^{-1}))</td>
<td>0.044(5)</td>
<td>(\leq 1.0)</td>
<td></td>
</tr>
<tr>
<td>(\lambda_2) (e(V^{-1})(\mu s^{-1}))</td>
<td>(\leq 1.0)</td>
<td>(\leq 1.0)</td>
<td></td>
</tr>
<tr>
<td>(\lambda_f) ((\alpha=1.0))</td>
<td>314(33)</td>
<td>314</td>
<td>[41]</td>
</tr>
<tr>
<td>(\lambda_f) ((\alpha=0.5)) ((\mu s^{-1}))</td>
<td>386(51)</td>
<td>386</td>
<td>[41]</td>
</tr>
<tr>
<td>(\lambda_f) ((\alpha=0.36))</td>
<td>461(87)</td>
<td>461</td>
<td>[41]</td>
</tr>
</tbody>
</table>

*Includes an estimated \(dd\mu\) finite-size correction of +0.01.

**Relativistic and other corrections (meV) to the non-relativistic binding energy \(\varepsilon_{11}^{0}\) of the \((J=1, \nu=1)\) level in the \(dd\mu\) molecule [50].**

| Vacuum polarization | 8.720 |
| Electromagnetic structure of nuclei | -1.675 |
| Relativistic | 1.650 |
| Finite size correction | 1.46 |
| Nuclear polarization | 0 |
| Total shift | 10.16 |
| Non-relativistic energy \(\varepsilon_{11}^{0}\) | -1974.985 [26] |
| Total energy \(\varepsilon_{11}\) | -1964.83 |
### Finite size correction

\[ \Delta E^{FS} = E^{dt\mu e} - \varepsilon^{dt\mu}_{11} - \varepsilon^{(dt\mu)-e}_{1s} \]

<table>
<thead>
<tr>
<th>Authors</th>
<th>( \Delta E^{FS} ) (meV)</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harston, Hara, Kino, Shimamura, Kamimura</td>
<td>0.50 ((E^{(1)}+E^{(2)}=18.253-17.752))</td>
<td>((dt\mu))</td>
</tr>
<tr>
<td></td>
<td>1.46 ((E^{(1)}+E^{(2)}=11.577-10.113))</td>
<td>((dd\mu))</td>
</tr>
<tr>
<td>This Work</td>
<td>0.25</td>
<td>((dt\mu))</td>
</tr>
<tr>
<td></td>
<td>2.31</td>
<td>((dt\mu))</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>((dd\mu))</td>
</tr>
<tr>
<td></td>
<td>1.70</td>
<td>((dd\mu))</td>
</tr>
</tbody>
</table>
Relative population of $\mu t$ hfs levels is a function of tritium concentration $C_t$.

Gershtein-Wolfenstein effect

Relative population of $p\mu t$ hfs levels is a function of $C_t$. 
In $\mu$CF-cycle nuclei approach each other during $10^{-9}$ s to the distance $\sim 10^{11}$ cm (what is equivalent to temperature $10^8$ K in hot fusion) and fusion takes place without heating and any macroscopic fields.
CONCLUSION

- $\mu CF$ is a nice and beautiful physics and obtained $\mu CF$ – knowledge should not disappear;
- $\mu CF$ - community have to prepare the book with the description of $\mu CF$ - physics, methods, results and applications;
- I am waiting for the contributions from the authors of this book chapters latest in October 2007;
- I wish the body health and soul equilibrium to all $\mu CF$ - community.

Good by!