$\mu CF - 07$

SUMMARY TALK

Leonid I. Ponomarev

RRC "Kurchatov Institute" and MUCATEX

73 participants

54 talks

27 laboratories

14 states

1937 - muon discovery

1947 - prediction of *μ* – catalysis

1957 - observation of *μ* – catalysis

1967 - discovery of *dμd* – resonance formation

1977 - prediction and observation of *dμt* – resonance formation

1987 - *μCF* – conference in Gatchina, where *μCF* – community was finally established.

Today the essential part of the *μCF* – community is involved in the different activities, but it is alive and still remembers those exciting time when we were much more younger.

μCF – meetings:

1984	**– Jackson Hall, Wyoming,**	***USA***
1986	**– Tokyo,**	***Japan***
1987	**– Gatchina,**	***Russia***
1988	**– Sanibel Island, Florida,**	***USA***
1989	**– Oxford,**	***UK***
1990	**– Wienna,**	***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

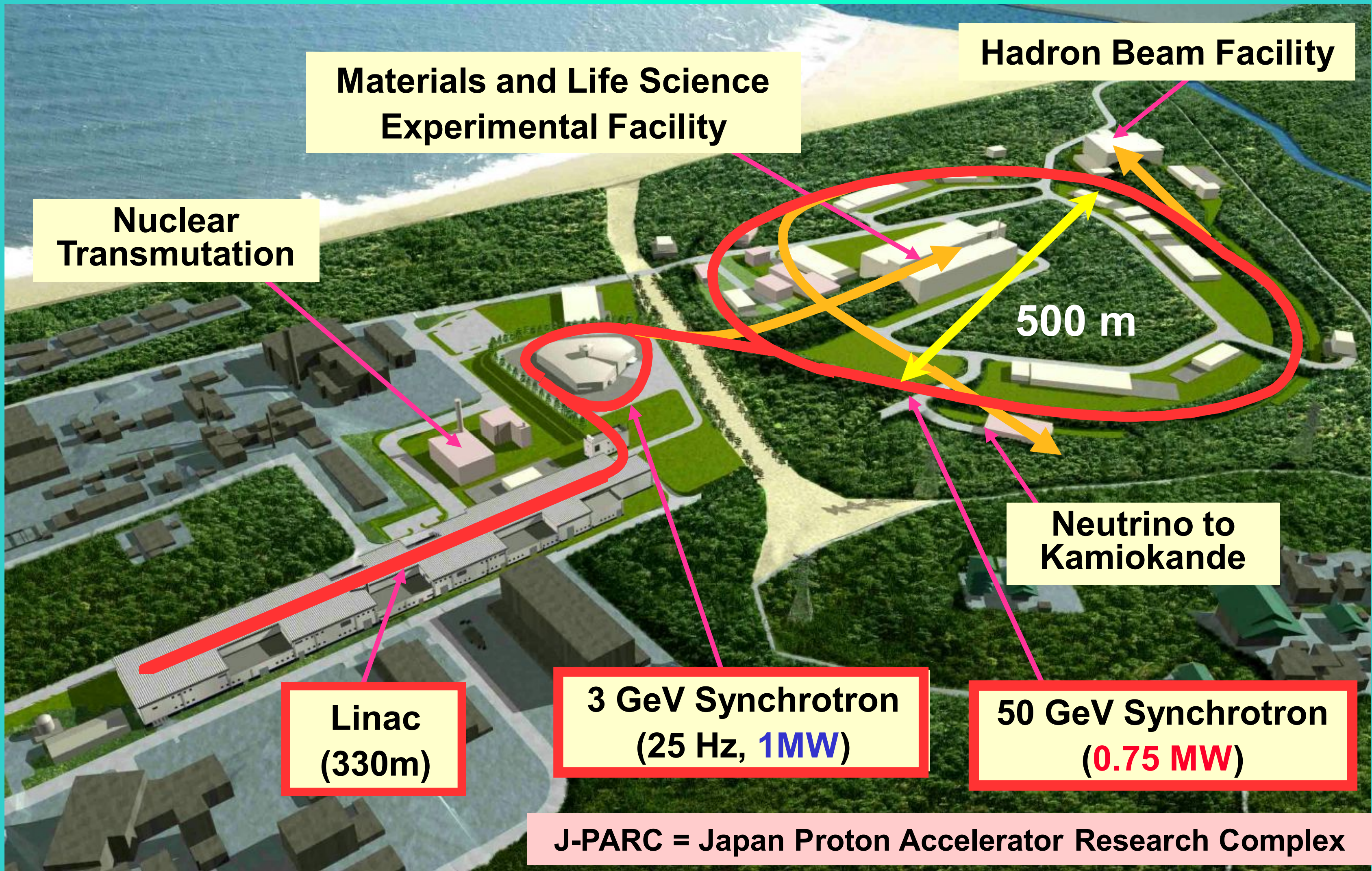
BULGARIA

INRNE Sofia

BELGIUM

Delft Tech. Univ.

J-PARC Facility



Joint Project between KEK and JAEA

MuCap

Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling g_P

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(MuCap Collaboration)

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(Dated: April 16, 2007)

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

Average of HBChPT calculations of Λ_S:

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

Apply new rad. correction (2.8%):

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

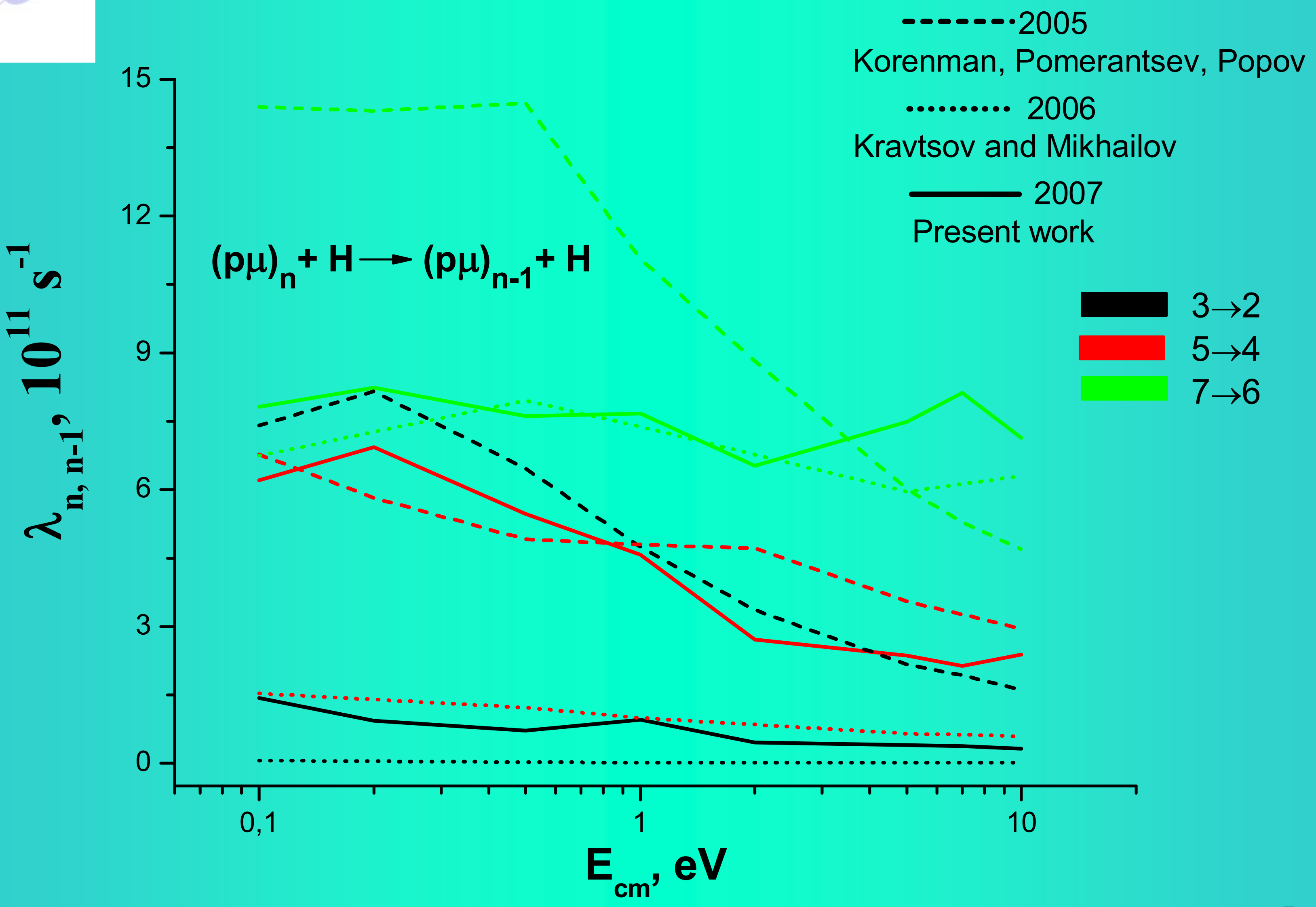
→

further sub percent theory required

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

$g_P = 7.3 \pm 1.1$ (MuCap 2007)

Coulomb de-excitation



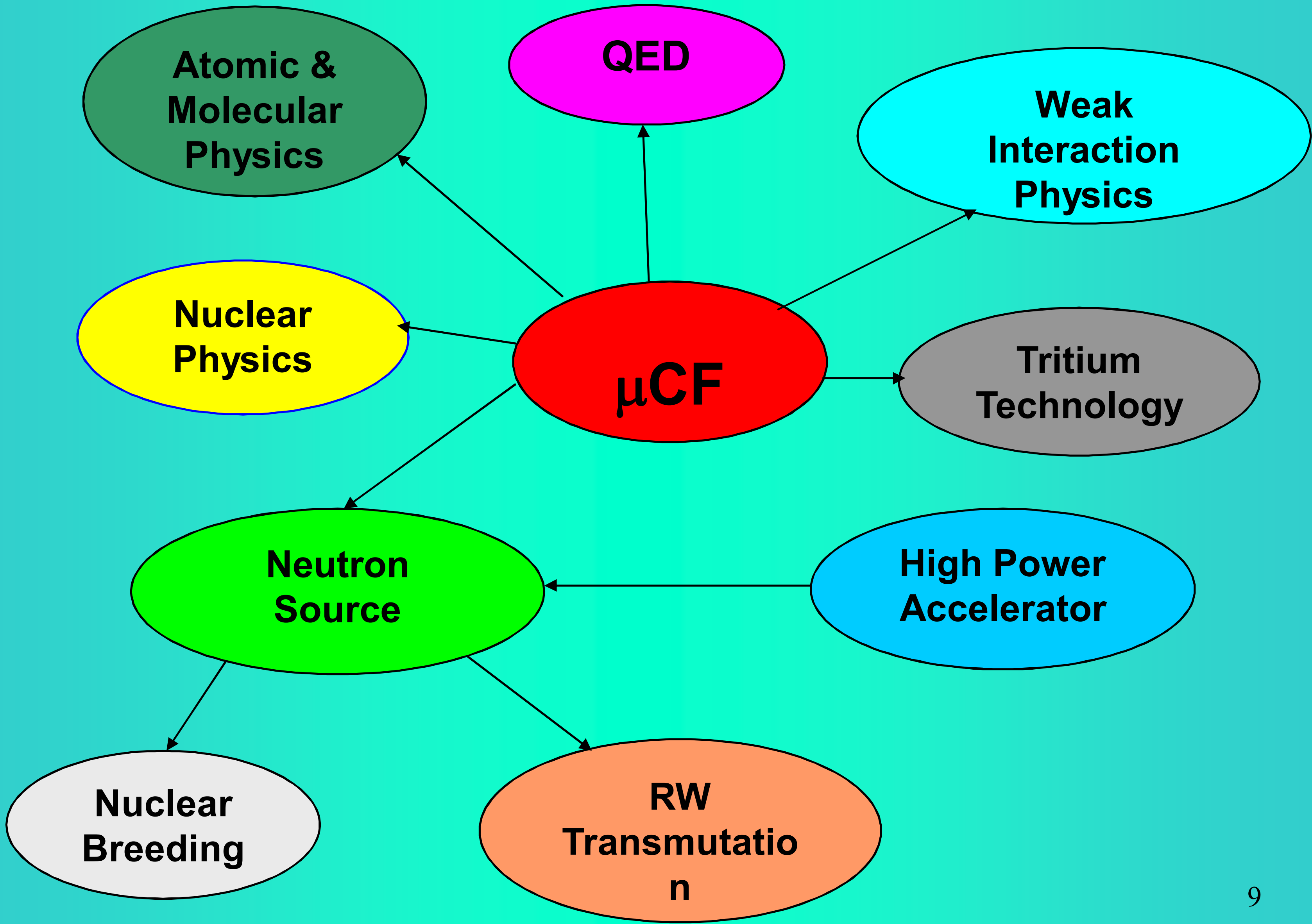
“A young woman is attractive by her beauty,
a grown lady is interesting by her children.”

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



μCF-applications in fundamental physics

- effective numerical codes;
- weak interaction physics;
- nuclear physics and astrophysics;
- $\overline{\mathrm{p}}$-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 $\bar{p}He^{+}$ system with the spectroscopic precision.

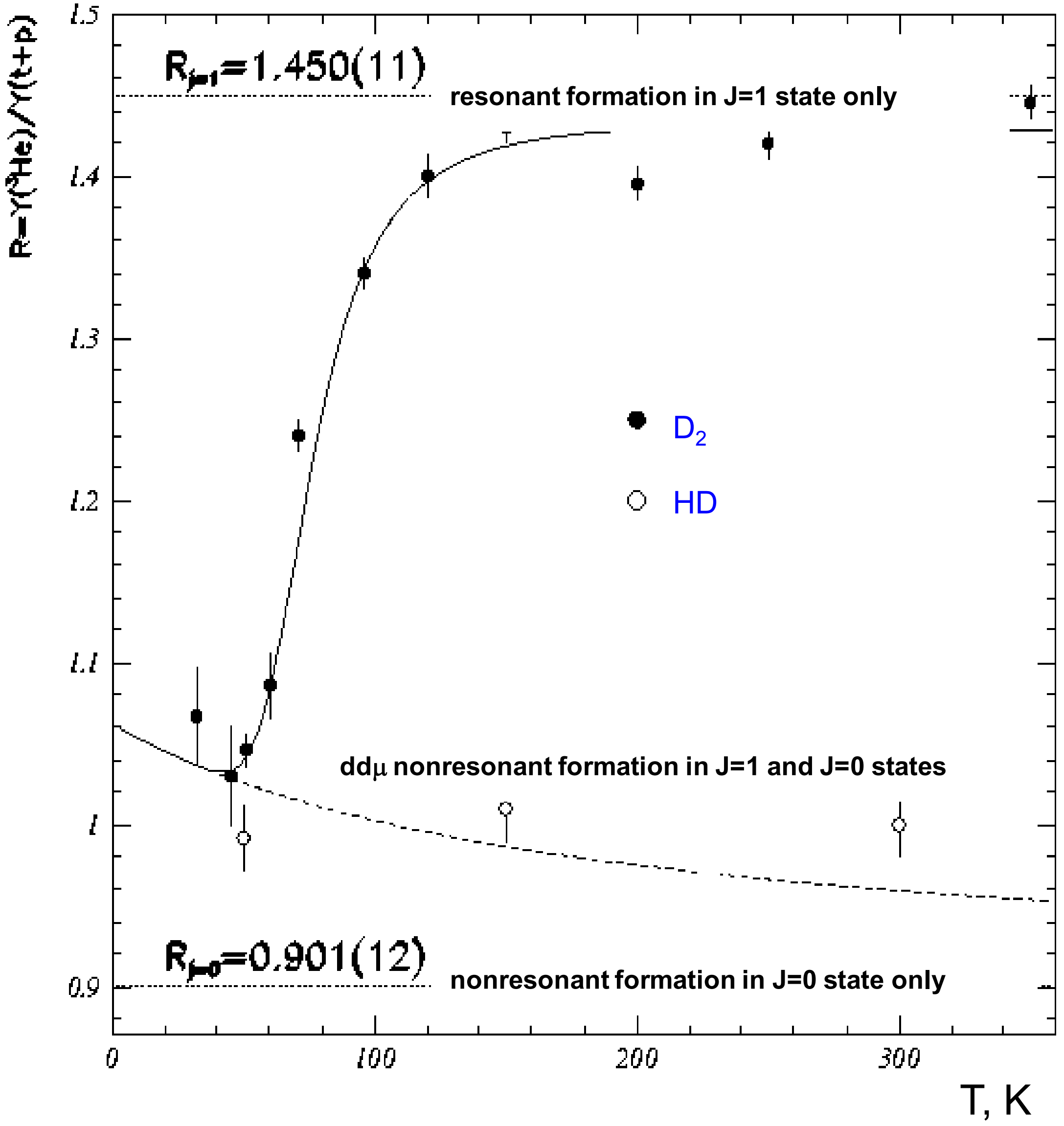
Nuclear physics and astrophysics

Measurements of nuclear fusion rates

- “at rest”;
- from a definite initial state.

Branching ratio

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

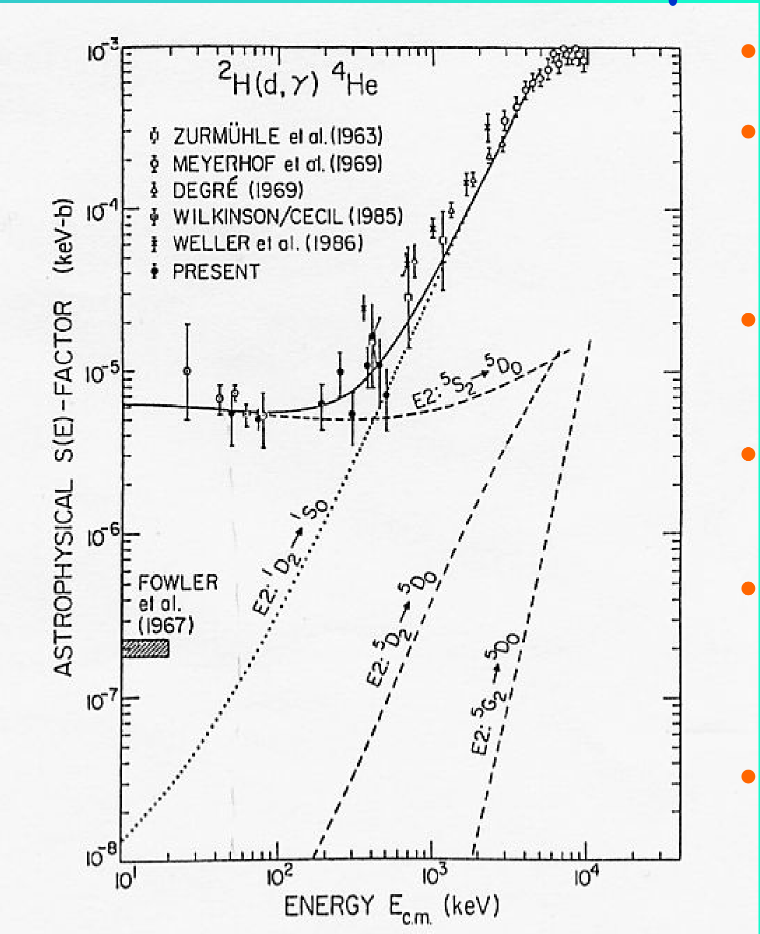


Measurements of branching ratio R as a function of temperature in D_2 and HD.

(PSI-PNPI-IMEP-LBNL-TUM-RRC KI– collaboration)

Muon catalyzed dd radiative capture

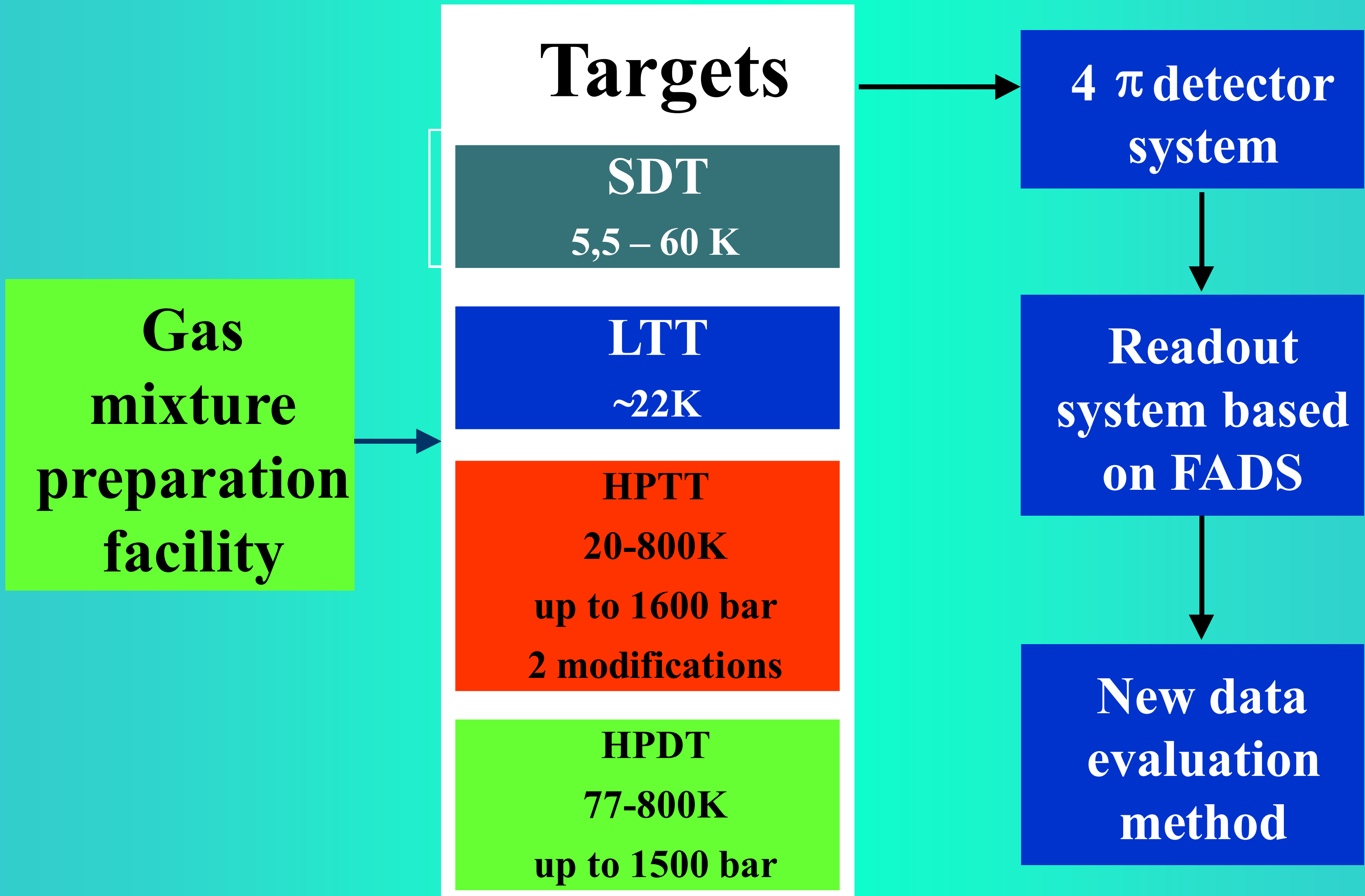
$dd\mu \rightarrow {}^4He + \mu + \gamma$



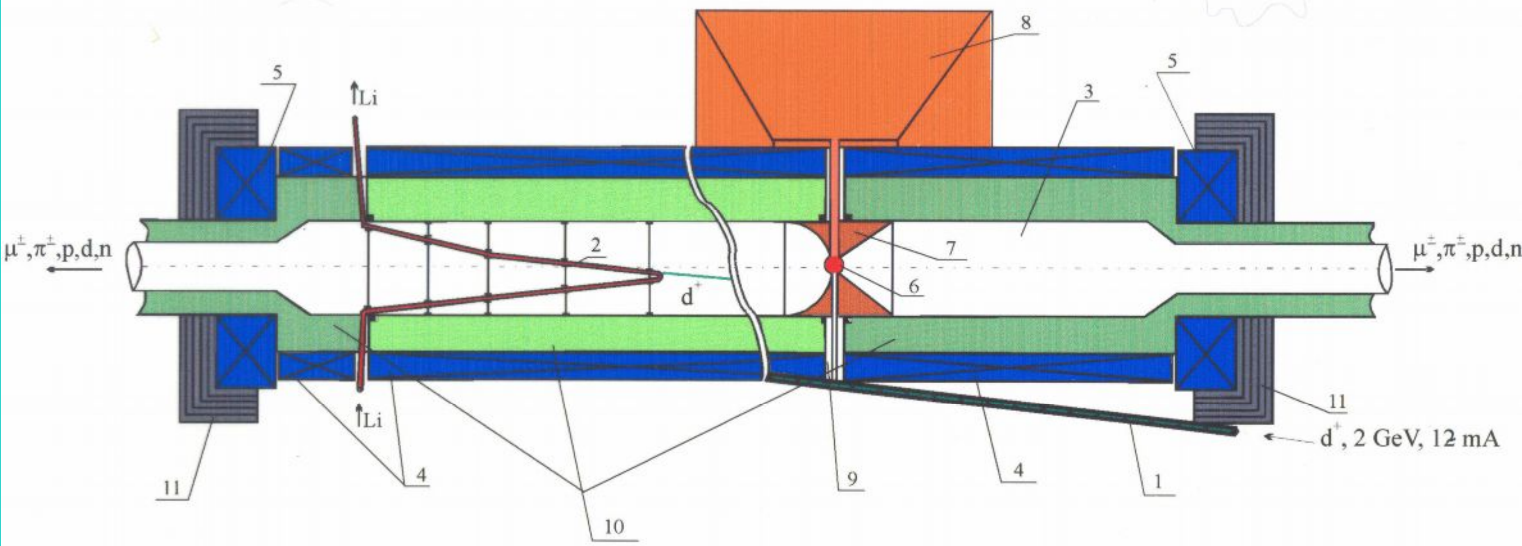
S-factor for $d(d,\gamma)^4He$

- Reaction $dd\mu \rightarrow {}^4He + \mu + \gamma$ 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 ^4He 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.

TRITON


Targets
SDT
5,5 – 60 K
LTT
~22K
HPTT
20-800K
up to 1600 bar
2 modifications
HPDT
77-800K
up to 1500 bar
Gas mixture preparation facility
4 π detector system
Readout system based on FADS
New data evaluation method

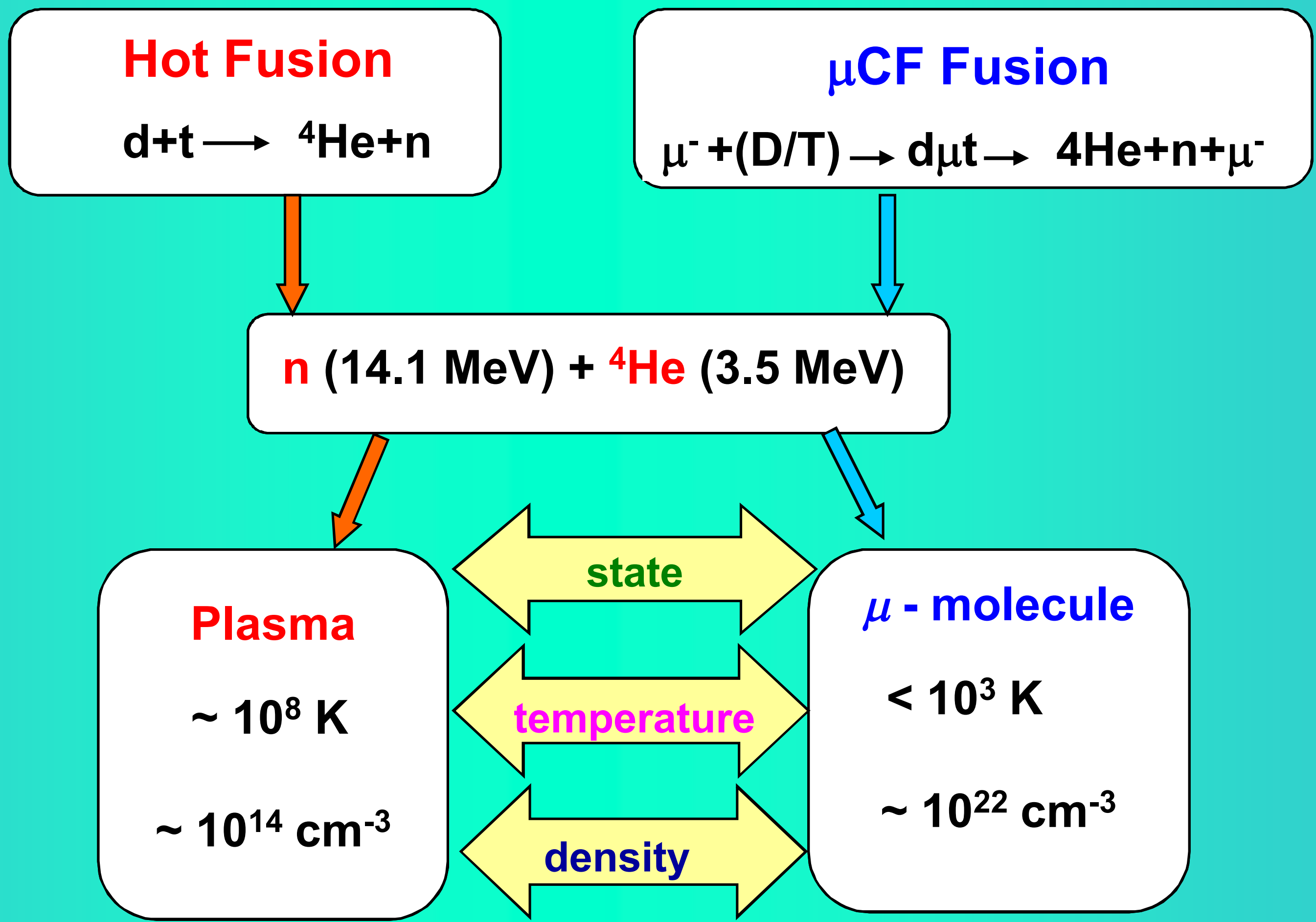
14 MeV Intense Neutron Source Based On Muon Catalyzed Fusion



1 - deutron beam chanel; 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 ≈ 10^{17} n/s;

Flux Φ≈ 10^{14} n/s·cm^2


Hot Fusion
d+t → 4He+n
μCF Fusion
μ- +(D/T) → dμt → 4He+n+μ-
n (14.1 MeV) + 4He (3.5 MeV)
Plasma
~ 10^8 K
~ 10^14 cm^-3
state
temperature
density
μ - molecule
< 10^3 K
~ 10^22 cm^-3

Fusion-Fission Hybride

Fission

$$n + U \rightarrow \text{fragments} + 200\ \text{MeV}$$

Fusion

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

Tritium Production

$$n + {}^{6}Li \rightarrow t + {}^{4}He$$

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

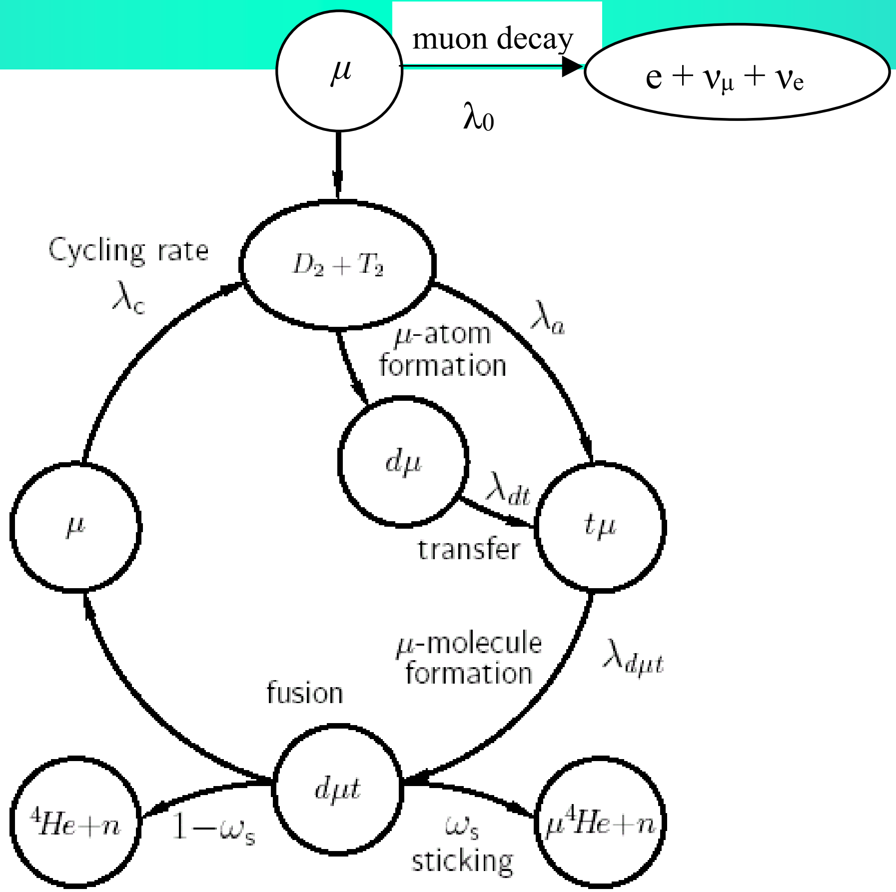
SUMMARY:

Fusion……………………………………	17.6 MeV;
Fission……………………………………	200 MeV;
Hot fusion breeder ………	700 MeV;
μCF - breeder…………………………	1000 MeV;
Tritium production……………………	200 MeV.

Main Characteristics of μCF-cycles .*)

Цикл	Реакции	λ_m, c^{-1}	λ_f, c^{-1}	ω_s	λ_{ab}, c^{-1}
pd	$p\mu \xrightarrow{\lambda_{pd}} d\mu \xrightarrow{\lambda_{pd\mu}} pd\mu \xrightarrow{\lambda_f} {}^3He + \mu^-$ $pd\mu \xrightarrow{\omega_s} \mu\,{}^3He + \gamma$	$5.8 \cdot 10^6$	$2.6 \cdot 10^5$	0.99	$1.7 \cdot 10^{10}$
pt	$p\mu \xrightarrow{\lambda_{pt}} t\mu \xrightarrow{\lambda_{pt\mu}} pt\mu \xrightarrow{\lambda_f} {}^4He + \mu^-$ $pt\mu \xrightarrow{\omega_s} \mu\,{}^4He + \gamma$	$6.8 \cdot 10^6$	$0.7 \cdot 10^5$	0.94	$0.7 \cdot 10^{10}$
dd	$d\mu \xrightarrow{\lambda_{d\mu d}} dd\mu \xrightarrow{\lambda_f} {}^3He + n + \mu^-$ $dd\mu \xrightarrow{\omega_s} \mu\,{}^3He + n$	$\sim 3 \cdot 10^6$	$4.3 \cdot 10^8$	0.12	-
dt	$d\mu \xrightarrow{\lambda_{dt}} t\mu \xrightarrow{\lambda_{dt\mu}} dt\mu \xrightarrow{\lambda_f} {}^4He + n + \mu^-$ $dt\mu \xrightarrow{\omega_s} \mu\,{}^4He + n$	$\sim 3 \cdot 10^8$	$1.2 \cdot 10^{12}$	0.0057	$2.8 \cdot 10^8$
tt	$t\mu \xrightarrow{\lambda_{tt\mu}} tt\mu \xrightarrow{\lambda_f} {}^4He + 2n + \mu^-$ $tt\mu \xrightarrow{\omega_s} \mu\,{}^4He + 2n$	$3 \cdot 10^6$	$1.5 \cdot 10^7$	0.14	-

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



μCF cycle in D/T mixtures.

Number of cycles:

$$Y_c = \frac{\lambda_c}{\lambda_0 + \omega_s \cdot \lambda_c}$$

Relativistic and other corrections (meV) to the nonrelativistic energies ε_{11}^{NR} of muonic molecular ions

	1992		2001	
	ddμ	**dtμ**	**ddμ**	**dtμ**
Nonrelativistic energy	-1974.82	-660.17	-1974.985	-660.336
Vacuum polarization	8.7	16.6	8.660	16.605
Electromagnetic structure of nuclei	-1.5	13.3	-1.675	13.183
Relativistic shift	1.4	0.1	1.660	0.853
Finite size corrections *(Ke)*	1.0	0.3	1.46	0.50
Nuclear polarization	0.0	-1.7	0.0	-1.7
Total shift	9.6	28.4	10.1	29.4
Total energy	**-1965.3**	**-631.8**	**-1964.9**	**-630.9**

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

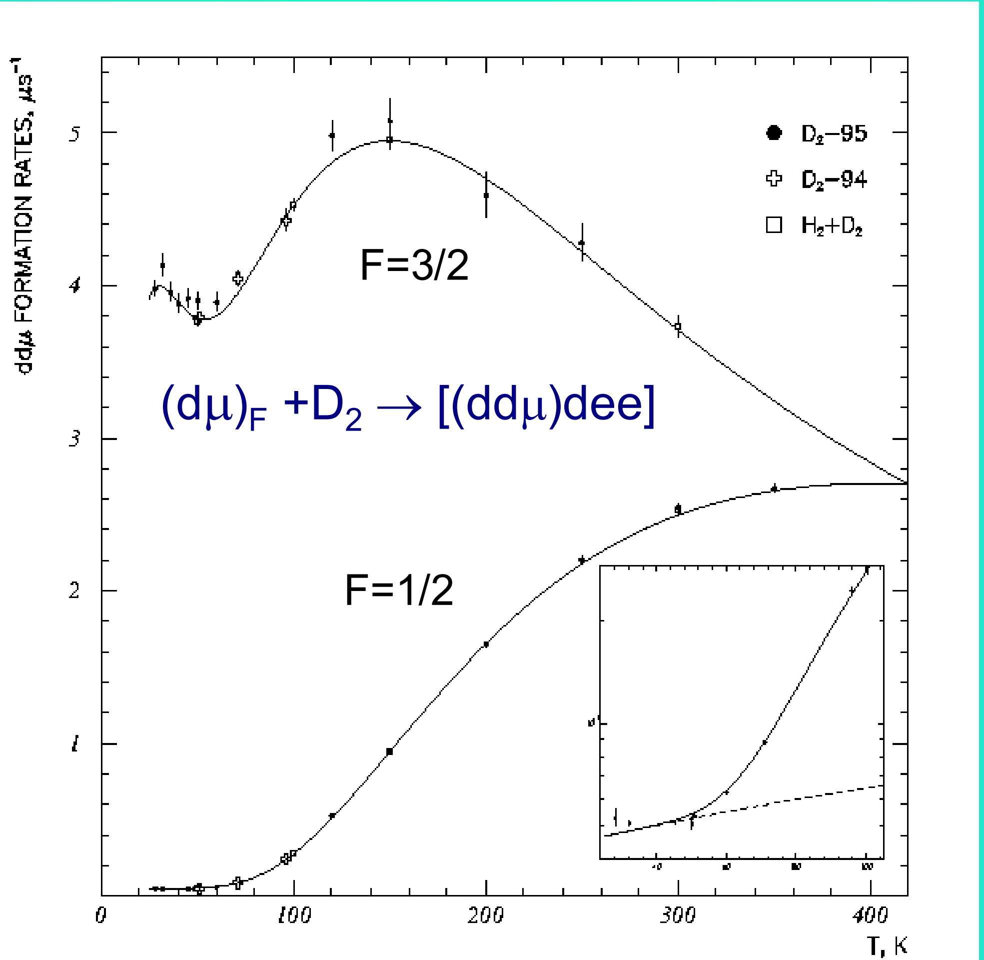
Binding energy of the weakly bound $dt\mu(11)$ molecular ion

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

* calculated with CODATA-86 recommended values;

** calculated with CODATA-98 recommended values.

ddμ resonant formation rates



FIT PARAMETERS	THEORY	FIT TO EXPERIMENT
$-\varepsilon_{11}$(eV)	1.9648	1.9626(3)
$\lambda_{fus}(10^6\,s^{-1})$	460	407(20)

(PSI-PNPI-IMEP-LBNL-TUM-RRC KI – collaboration)

μ-molecule nonrelativistic binding energies ε_{Jv}, eV of the states $(Jv)^*$

Molecule\(Jv)	(00)	(01)	(10)	(11)	(20)	(30)
$p\mu p$	253.152	-	107.256	-	-	-
$p\mu d$	221.549	-	97.498	-	-	-
$p\mu t$	213.840	-	99.127	-	-	-
$d\mu d$	325.074	35.844	266.682	**1.975**	86.434	-
$d\mu t$	319.140	34.834	232.472	**0.660**	102.643	-
$t\mu t$	362.910	83.771	289.142	45.206	172.526	48.70

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

The main characteristics of μCF-processes*

Rates	Numerical value, $\lambda, 10^6 \cdot s^{-1}$ at $\varepsilon = 0.04$eV	Reaction	Remarks
λ_a	$\sim 10^7$	$\mu^- + H_2 \to p\mu + H + e^-$	Collision energy dependent:
λ_{pd} λ_{pt} λ_{dt}	$1.6 \cdot 10^4$ $7.1 \cdot 10^3$ $2.5 \cdot 10^2$	$p\mu + d \to d\mu + p$ $p\mu + t \to t\mu + p$ $d\mu + t \to t\mu + d$	at $\varepsilon > 1$eV at $\varepsilon > 1$eV at $\varepsilon > 0.1$eV
λ_p λ_d λ_t	$1.7 \cdot 10^4$ 37 $1.2 \cdot 10^3$	$(p\mu)_{F=1} + p \to (p\mu)_{F=0} + p$ $(d\mu)_{F=3/2} + d \to (d\mu)_{F=1/2} + d$ $(t\mu)_{F=1} + t \to (t\mu)_{f=0} + t$	at $\varepsilon > 1$eV at $\varepsilon > 0.1$eV at $\varepsilon > 1$eV
$\lambda_{p\mu p}$ $\lambda_{p\mu d}$ $\lambda_{p\mu t}$ $\lambda_{t\mu t}$	1.8 5.6 6.4 2.6	$p\mu + H_2 \to [(p\mu p)pe]^+ + e^-$ $d\mu + H_2 \to [(p\mu d)pe]^+ + e^-$ $t\mu + H_2 \to [(p\mu t)pe]^+ + e^-$ $t\mu + T_2 \to [(t\mu t)te]^+ + e^-$	
$\lambda^{nr}_{d\mu d}$ $\lambda^{nr}_{d\mu t}$	~ 1 ~ 8	$d\mu + D_2 \to [(d\mu d)de]^+ + e^-$ $t\mu + D_2 \to [(d\mu t)de]^+ + e^-$	
$\lambda_{d\mu d-p}$ $\lambda_{d\mu d-d}$ $\lambda_{d\mu d-t}$	2.7	$d\mu + HD \to [(d\mu d)pee]^*$ $d\mu + D_2 \to [(d\mu d)dee]^*$ $d\mu + DT \to [(d\mu d)tee]^*$	Temperature and energy dependent
$\lambda_{d\mu t-p}$ $\lambda_{d\mu t-d}$ $\lambda_{d\mu t-t}$	$\sim 3 \cdot 10^2$	$t\mu + HD \to [(d\mu t)pee]^*$ $t\mu + D_2 \to [(d\mu t)dee]^*$ $t\mu + DT \to [(d\mu t)tee]^*$	
$\lambda^f_{p\mu d}$ ω_{pd}	0.26 0.86	$p\mu d \to \mu^3He + \gamma$	
$\lambda^f_{p\mu t}$ ω_{pt}	0.07 0.94	$p\mu t \to \mu^4He + \gamma$	
$\lambda^f_{d\mu d}$ ω^n_{dd} $\lambda^f_{d\mu d}$ ω^p_{dd}	430 0.132 430 $< 10^{-3}$	$d\mu d \to \mu^3He + n$ $d\mu d \to \mu t + p$	Branching ratio of mirror channels $\beta = \frac{^3He+n}{t+p} = 1.46$ at $T > 150$ K The effective striking probability $\omega^0_{dd} = \frac{\beta}{1+\beta}\omega^n_{dd} = 0.078$
$\lambda^f_{d\mu t}$ ω_{dt}	$1.1 \cdot 10^6$ $0.46 \cdot 10^{-2}$	$d\mu t \to \mu^4He + n + n$	
$\lambda^f_{t\mu t}$ ω_{tt}	15 0.12	$t\mu t \to \mu^4He + n + n$	
R_{dd} R_{dt}	0.05 0.3	$\mu^3He + d \to \begin{cases} \nearrow\ ^3He + d + \mu^- \\ \searrow\ ^3He + d\mu \end{cases}$ $\mu^4He + d \to \begin{cases} \nearrow\ ^4He + d + \mu^- \\ \searrow\ ^4He + d\mu \end{cases}$	at liquid hydrogen density

* All the rates are normalized to the liquid hydrogen density $\varphi_0 = 4.25 \cdot 10^{22} cm^{-3}$

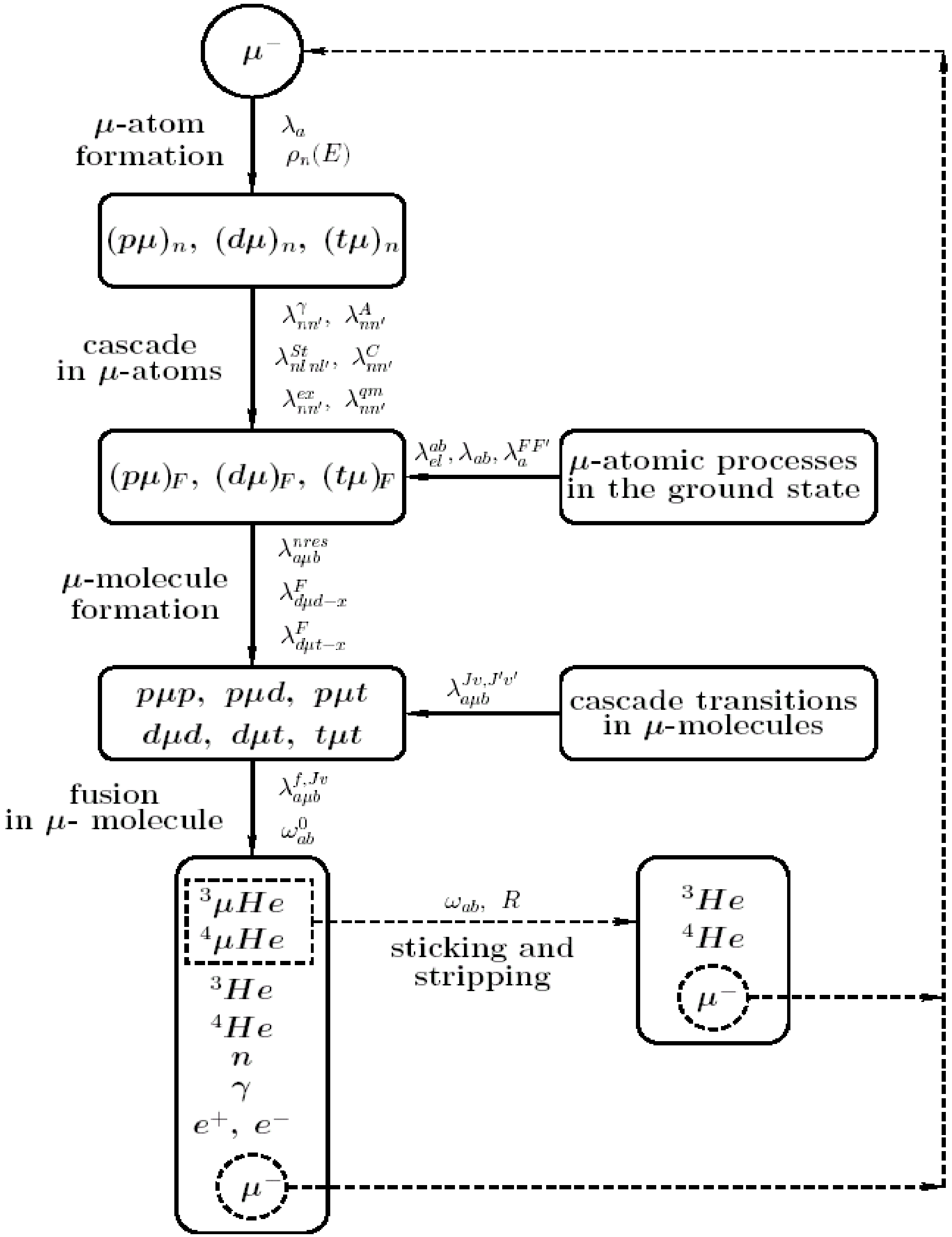
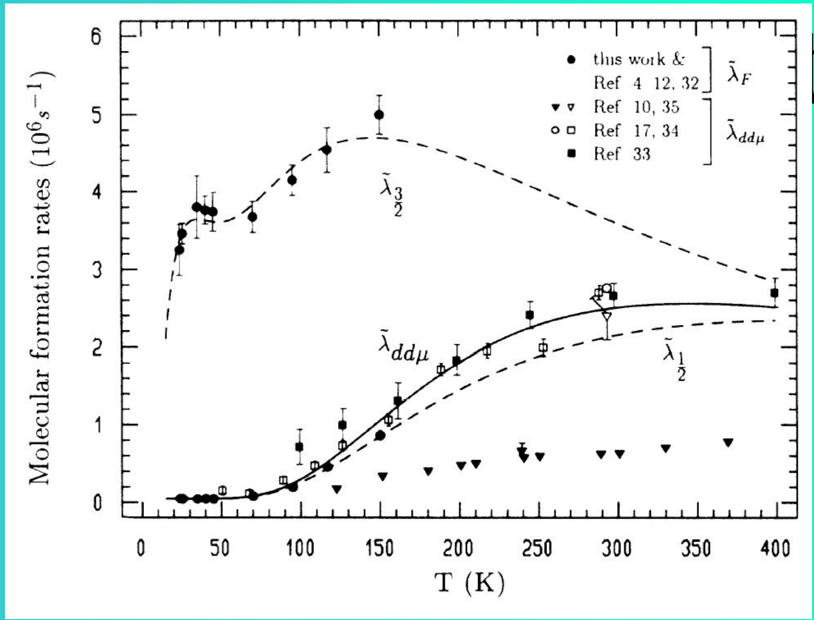
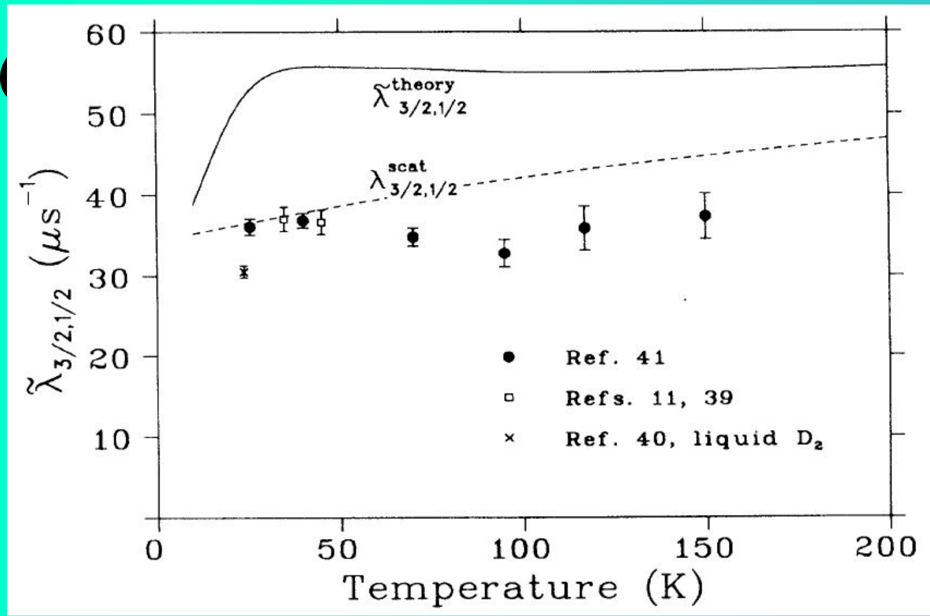


Figure 5: Scheme of μCF processes in $H/D/T$ mixtures.





Rates for
LH_2 density

TABLE V. Results of the fit to $\tilde{\lambda}_{1/2}$ and $\tilde{\lambda}_{3/2}$ and theoretical values.

Quantity	Fit	Calculation	Ref.
ε_{11} (meV)	$-1966.1(2)$	-1966.2[a]	[34]
λ_1 (μs^{-1})	0.044(5)		
λ_2 ($eV^{-1}\mu s^{-1}$)	$\lesssim 1.0$		
$\tilde{\lambda}_f$ ($\alpha=1.0$)	314(33)		
$\tilde{\lambda}_f$ ($\alpha=0.5$) (μs^{-1})	386(51)		
$\tilde{\lambda}_f$ ($\alpha=0.36$)	461(87)		

[a]Includes an estimated $dd\mu$ finite-size correction of +(

TABLE XIII: Relativistic and other corrections (meV) to the non-relativistic binding energy ε_{11}^{nr} of the (J= 1, ν = 1) level in the ddμ 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 ε_{11}^{nr}	-1974.985 [26]
Total energy ε_{11}	**-1964.83**

10^{-7} of muonic Rydberg energy

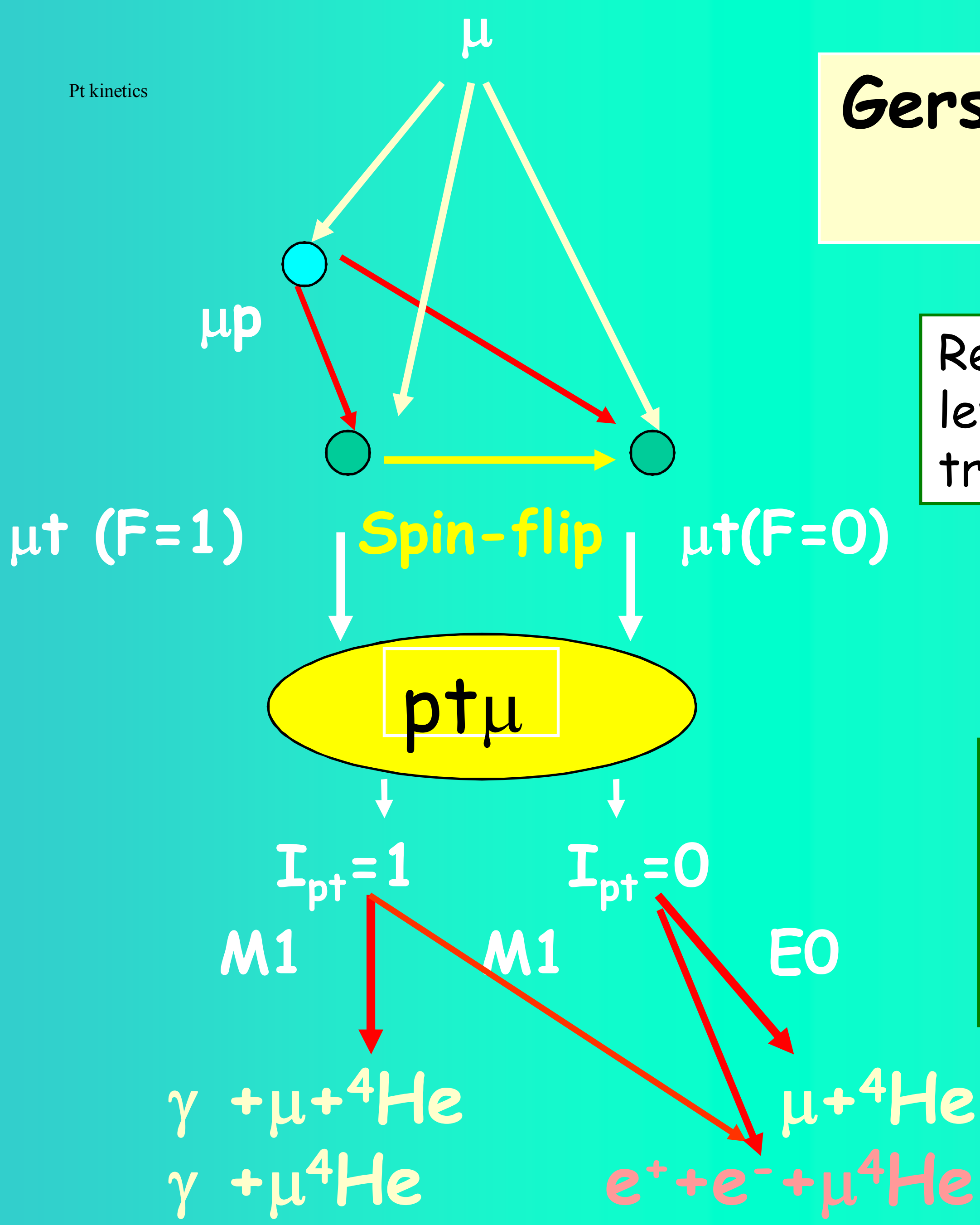
Finite size correction

$$\Delta E^{\mathrm{FS}} = E^{dt\mu e} - \varepsilon_{11}^{dt\mu} - \varepsilon_{1s}^{(dt\mu)-e}$$

Authors	ΔE^{FS} **(meV)**	Syste
Harston, Hara, Kino, Shimamura, Kamimura	0.50 ($E^{(1)}+E^{(2)}$=18.253–17.752) 1.46 ($E^{(1)}+E^{(2)}$=11.577–10.113)	($dt\mu$) ($dd\mu$
This Work	0.25 **2.31** 0.30 **1.70**	($dt\mu$ **($dt\mu$** (dd **(dd**

Gershtein-Wolfenstein effect

Pt kinetics



Relative population of μt hfs levels is a function of tritium concentration C_t

Relative population of pμt hfs levels is a function of C_t

Energy	Transition	Time	Distance
	$\mu + t$		
		$\tau \sim 10^{-12}$ s	
$\varepsilon \sim 0.1$–1 eV	$\mu t + d$		$a \sim 10^{-8}$ cm
		$\tau \sim 10^{-9}$ s	
$\varepsilon \sim 1$ eV	$dt\mu$ (J=1, v=1)		$a \sim 10^{-10}$ cm
		$\tau \sim 10^{-11}$ s	
$\varepsilon \sim 100$ eV	$dt\mu$ (J=1, v=0)		$a \sim 10^{-11}$ cm
		$\tau \sim 10^{-12}$ s	
$\varepsilon \sim 10$ MeV	$^{4}He + n + \mu$		$a \sim 10^{-13}$ cm

In μCF-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

- ***μCF*** **is a nice and beautiful physics and obtained *μCF* – knowledge should not disappear;**
- ***μCF*** **- community have to prepare the book with the description of *μCF* - 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 *μCF* - community.**

Good by!