Fusion μ-catalysée en plasmas ultradense

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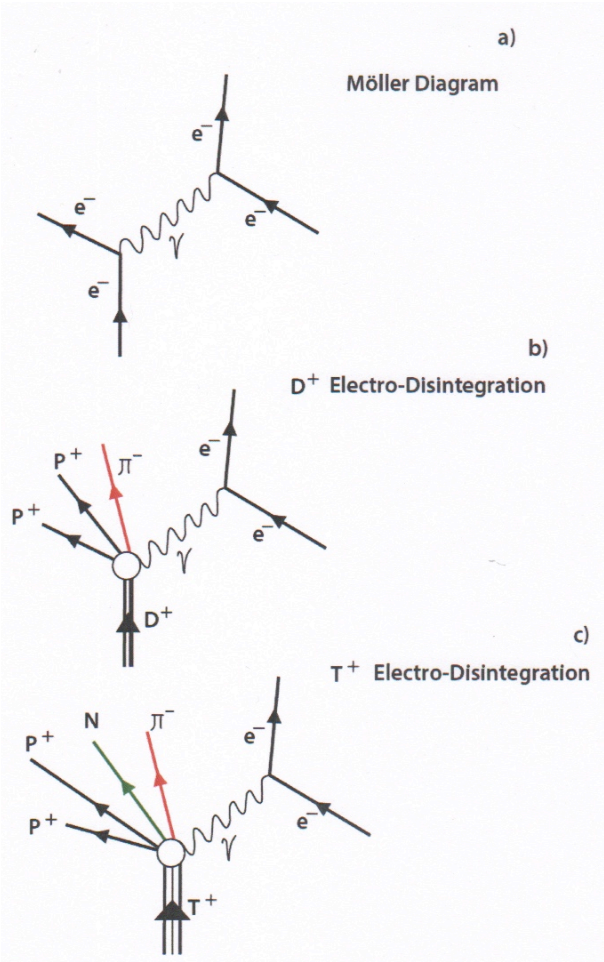


Figure 1: (color online) (a) Electron-electron covariant Möller diagram. (b) D-Electron-disintegration and (c) T-Electron-disintegration. In (b) and (c) π^- appears when REB energy $E_b \geq 150$ MeV.

- Ralentissement des $\pi^-(\mu^-)$ à quelque MeV en **plasmas ultradenses** :

  - WDM, 5.64×10^{23}/cc, 1.75 eV

  - FIS, 10^{26}/cc, 0.1 et 1 keV

- Formation d'ions moléculaires hydrogenoïdes

- Problématique du collage ('Stincking')

- Taux de production d'énergie rapportée au coût de production du π^-.

ANTICIPATION

- 134 DT fusion en WDM sur 500 psec

- 20 DT fusion en FIS sur 20 psec

Longueurs pertinentes

$$n_e \sim 10^{26}\ e - \mathrm{cm}^{-3} \qquad T \sim 1\ keV$$

$$a_{ii} = \left(\frac{4}{3}\pi n_i\right)^{-1/3} \sim 1.33 \times 10^{-9}\mathrm{cm}$$

Longueur de Debye $\sim 2.35 \times 10^{-9}$ cm

Rayon de Bohr (electron) $= 5.29 \times 10^{-9}$ cm

Rayon de Bohr (pion) $= 1.94 \times 10^{-11}$ cm

Π-D and Π-T atoms hardly affected by electron Debye-screening.

RECOMBINAISON RADIATIVE $\Pi^- - D + (T^+)$ (R_2)

$$\sigma_0 = (2^7 \pi e^2 h / 3 m'^2_\pi c^3 g^2) e^{(-4/g) tan^{-1}} g (1+g^2)^{-2} (1-e^{-2\pi/g})^{-1}$$

g is the ratio of the initial translational energy of the electron to the energy of ionization of the *exoH* atom. For low velocities the cross becomes infinite:

$$\sigma_0 \sim (2^7 \pi e^2 h / 3 e_1^4 m'^2_\pi c^3) g^{-2} \sim (V_\pi / c)^{-4} \quad e_i = 2.718...$$

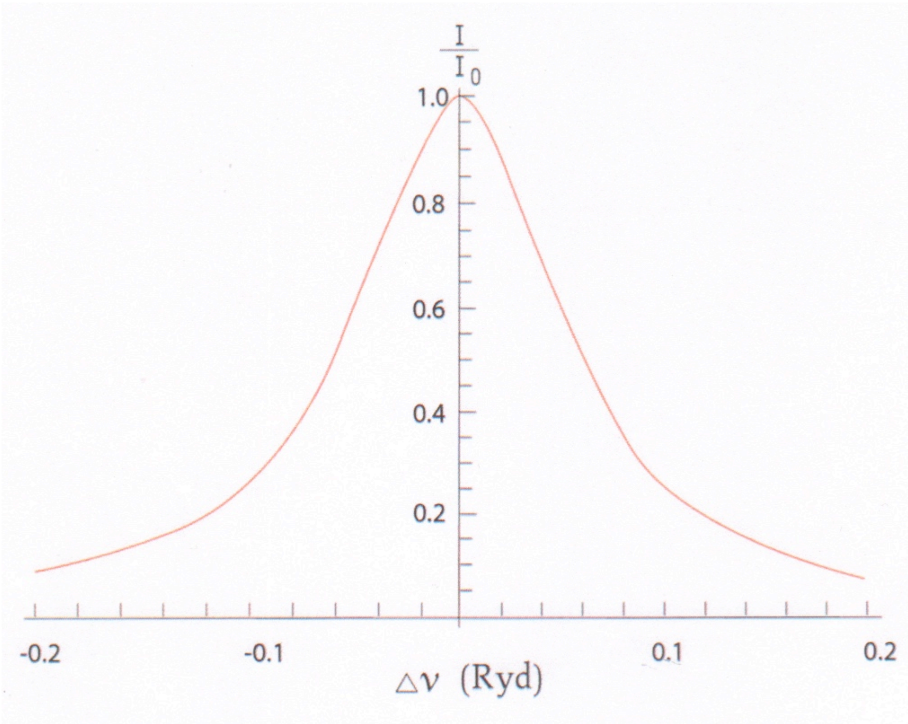
For high velocities it is given by

$$\sigma_0 \sim (64 e^2 h / 3 m'^2_\pi c^3) g^{-5},$$

where

$$g = \frac{1}{2} \cdot \frac{139.5 \times 10^6 (V_\pi / c)^2}{\frac{273 \times 27.2}{2n^2}}$$
$$= 18787\ n^2 \left(\frac{V_\pi}{c} \right)^2$$

J. R. Oppenheimer. Zeit. f. Physik **41**, 268 (1927); Phys. Rev. **31**, 349 (1928).



X-Ray (Stark) line profiles emitted by D/T μ exoatoms in FIS plasmas (Ne= $10^{26}/cc$, T= 1 keV).
Energies are in Ryd = 2812.35 eV (muon a.u.).
Lyman α with unperturbed $\lambda = 6.146\mathring{A}$.

Taux de Recombinaison D/T ions - $\mu\,\gamma^{\mu}(sec^{-1}) = N_{D/T\bar{\sigma}_0 v}$
in terms of exoatom main quantum number n and Maxwell
averaged $\bar{\sigma}_0$ taken down to 10^{-13} V_{th}

n	WDM ($N_{D/T} = 5.64 \times 10^{23}/cc, T = 1.75eV$)	FIS($N_{D/T} = 10^{26}/cc$)	
		100 eV	1 keV
1	6.109×10^{18}	2.50×10^{18}	7.92×10^{16}
2	3.82×10^{17}	1.564×10^{17}	4.95×10^{15}
3	7.54×10^{16}	3.09×10^{16}	9.77×10^{14}
4	2.39×10^{16}		
5	9.77×10^{15}		
6	4.71×10^{15}		

Recombinaison 3-corps $D/T - \mu - D/T$ via la polarisabilité α et le dipole magnétique de l'exoatome $D/T - \mu$

$$\boxed{\bar{K} = (2/\mu^{1/2})[\alpha^{1/2} + c\mu_D(2/_B T)^{1/2}]}$$

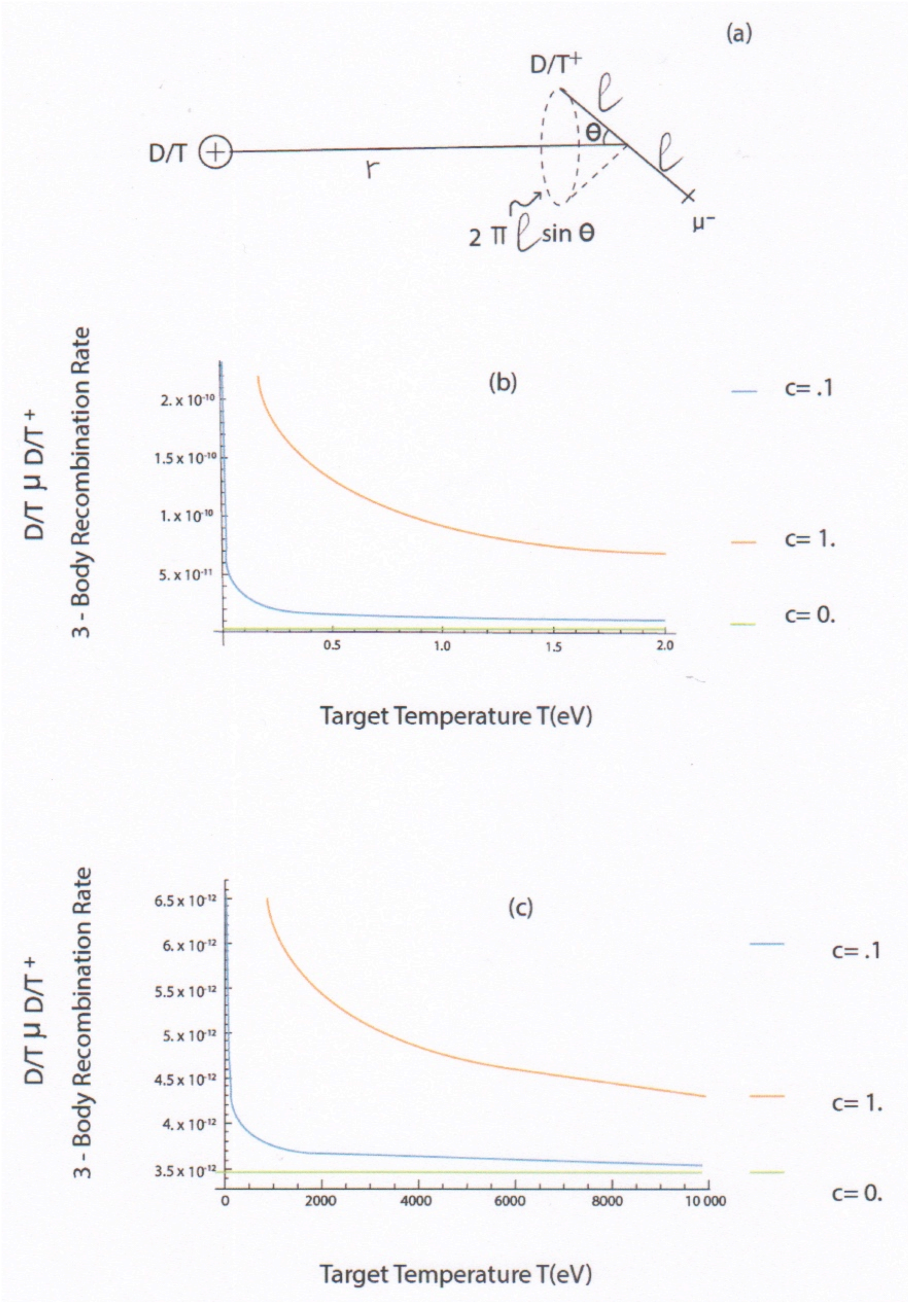
with

$$\alpha = \frac{1}{n}\sum_{\ell=0}^{n-1}\left[a_0^{n\ell} + 2\sum_{m=0}^{\ell} a_2^{n\ell}\,\frac{3m^2 - \ell(\ell+1)}{\ell(2\ell-1)}\right] cm^3,$$

where

$$a_0^{n\ell} = \frac{n^4}{4}[4n^2 + 14 + 7\ell(\ell+1)]$$
$$a_2^{n\ell} = \frac{-n^4\ell}{4(2\ell+3)}[3n^2 - 9 + 11\ell + \ell(\ell+1)]$$

and dipole moment $\mu_D = \frac{ea_0^{\mu}}{2n}\sum_{\ell=0}^{n-1}(3n^2 - \ell(\ell+1)$ averaged over (n,ℓ) levels through Holtsmark Stark-mixing, with tuning parameter c featuring either a locked dipole $(c = 1)$ or a rotating one $(c = 0.1)$.


(a)
D/T$^+$
D/T
r
2 π ℓ sin θ
μ$^-$
(b)
D/T μ D/T +
3 - Body Recombination Rate
Target Temperature T(eV)
c= .1
c= 1.
c= 0.
(c)
D/T μ D/T +
3 - Body Recombination Rate
Target Temperature T(eV)
c= .1
c= 1.
c= 0.

RECOMBINAISON 3 corps $D/T - \mu - D/T(psec^{-1})$

Three-body capture rates $N_{D/T}\bar{K}$ (psec^{-1}) in terms of exoatom main quantum number n and amount of dipole contribution c.

a) WDM target ($T = 1.75eV, N_{D/T} = 5.64 \times 10^{23}/cc$)

n	1	2	3	4	5	6
c=0.1	1.34	5.71	14.45	28.85	50.2	79.73
c=1	10.55	39.5	89.2	161	256	375.5

b) FIS target ($T = 1keV, N_{D/T} = 10^{26}/cc$)

n	1	2	3	4
c=0.1	64.32	374.46	1151.3	2757.0
c=1	132.64	624.95	1705.4	3601.25

c) FIS target ($T = 100eV, N_{D/T} = 10^{26}/cc$)

n	1	2	3	4
c=0.1	80.73	434.64	1824.44	2857.3
c=1	296.8	1226.8	3036.75	5953.83

Analyse Dynamique

$$\frac{dN_{\mu}(t)}{dt} = -(2\lambda_{\frac{D}{T}\mu}+\lambda_0^{\mu})N_{\mu}(t)+2\lambda_{\frac{D}{T}\mu\frac{D}{T}}N_{\frac{D}{T}\mu}(t),$$

$$\frac{dN_{\mu}(t)}{dt} = 2\lambda_{\frac{D}{T}\mu\frac{D}{T}}N_{D/T}N_{\mu}(t)-2(\lambda_{\frac{D}{T}\mu}+\lambda_0^{\mu})N_{\frac{D}{T}\mu}(t)$$

expressed more compactly under the form

$$\frac{dN_{\mu}(t)}{dt} = -a_1N_{\mu}(t) + 2b_1N_{D/T\mu}(t),$$

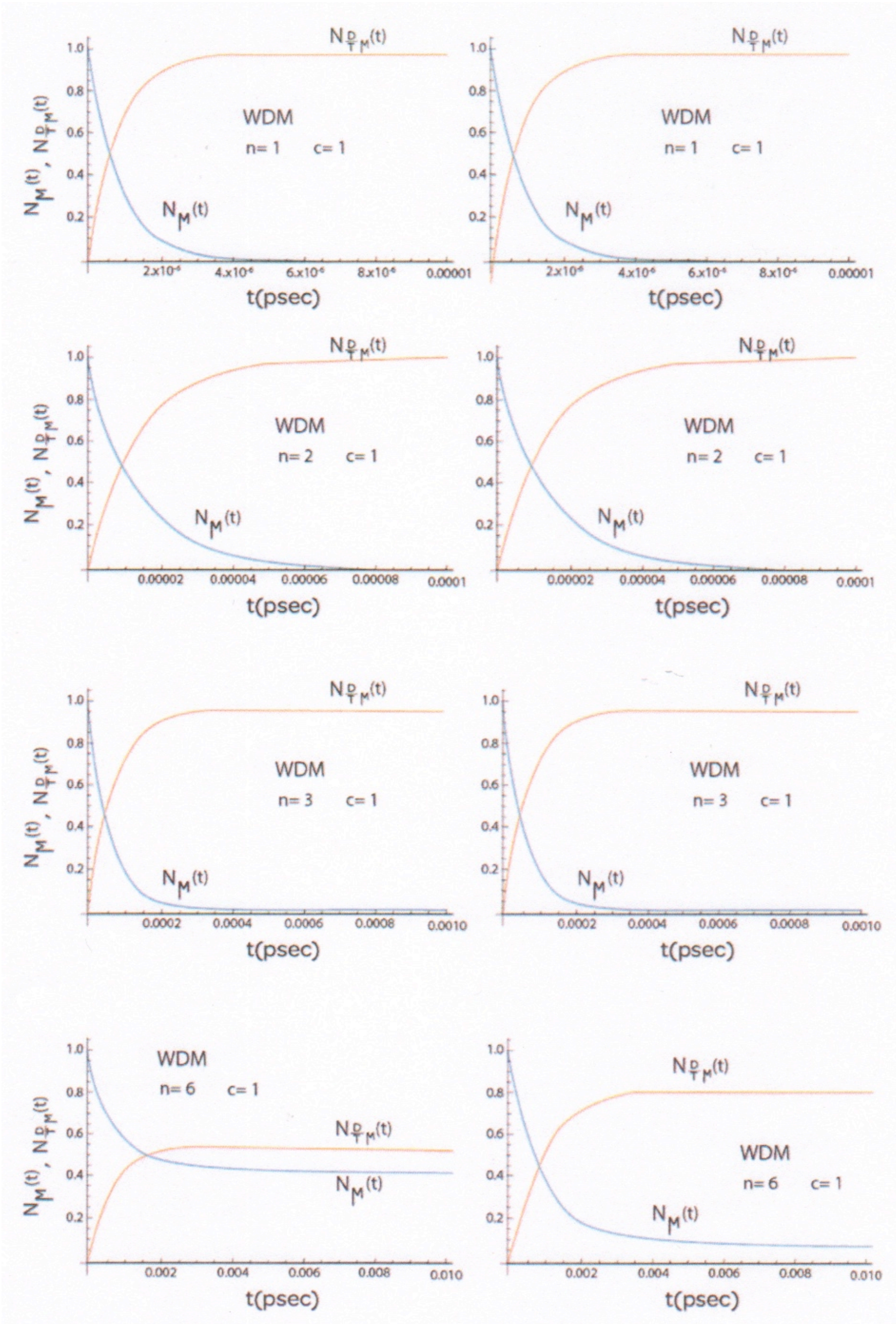
$$\frac{dN_{\mu}(t)}{dt} = 2a_2N_{\mu}(t) - 2b_2N_{D/T\mu}(t),$$

where

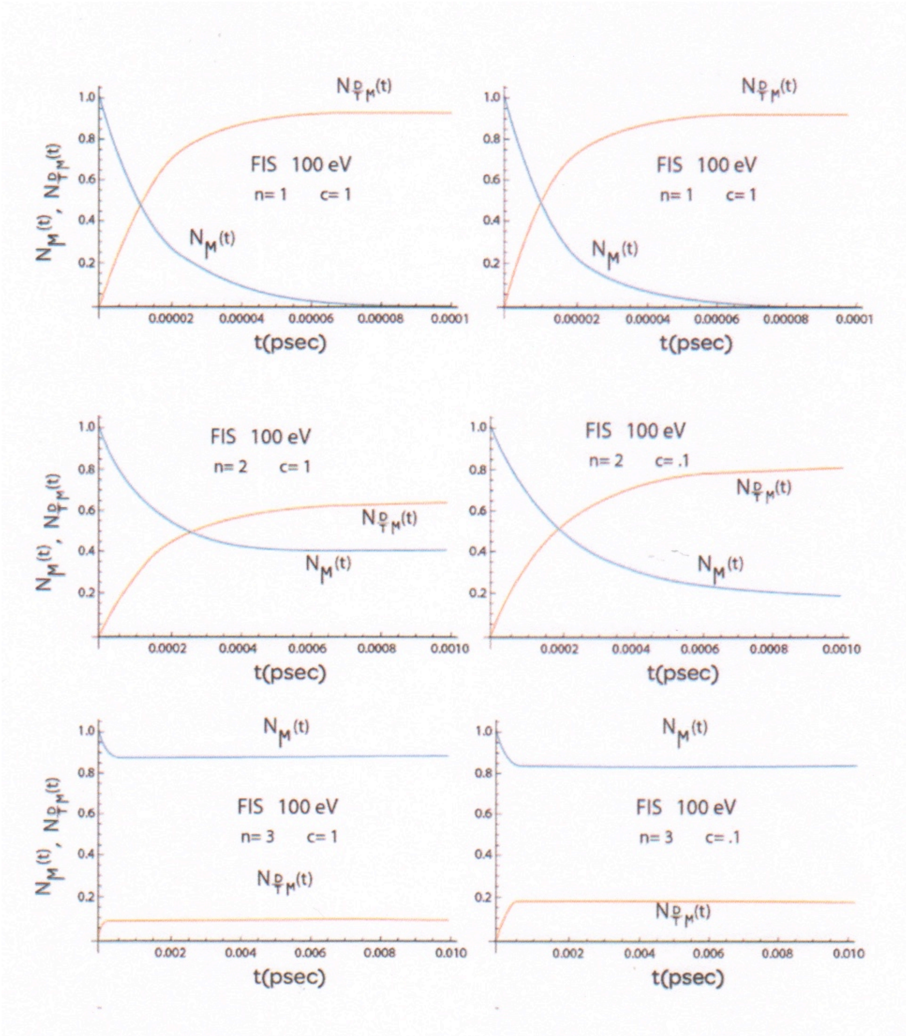
$$a_1 = 2\lambda_{D/T\mu}N_{D/T} + \lambda_0^{\mu},$$
$$a_2 = \lambda_{D/T\mu}N_{D/T},$$
$$b_1 = \lambda_{D/T\mu D/T}$$

and

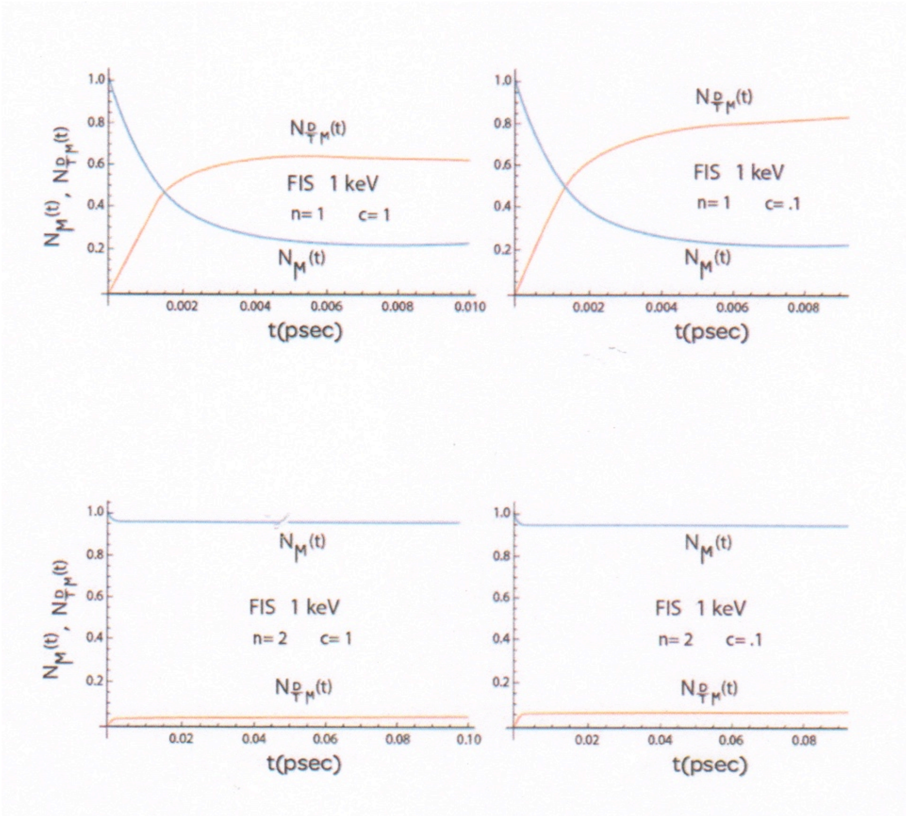
$$b_2 = b_1 + \lambda_0^{\mu}$$



WDM
n= 1 c= 1
WDM
n= 1 c= 1
WDM
n= 2 c= 1
WDM
n= 2 c= 1
WDM
n= 3 c= 1
WDM
n= 3 c= 1
WDM
n= 6 c= 1
WDM
n= 6 c= 1
t(psec)



FIS 100 eV
n= 1 c= 1
FIS 100 eV
n= 1 c= 1
FIS 100 eV
n= 2 c= 1
FIS 100 eV
n= 2 c= .1
FIS 100 eV
n= 3 c= 1
FIS 100 eV
n= 3 c= .1
t(psec)


FIS 1 keV
n= 1 c= 1
FIS 1 keV
n= 1 c= .1
FIS 1 keV
n= 2 c= 1
FIS 1 keV
n= 2 c= .1
t(psec)

PROBABILITE DE REACTIVATION (μ^-) R=1-exp(-JR)

(a) $He_\mu^+(n=1)$

WDM		FIS			
JR	R	100 eV		1 keV	
		JR	R	JR	R
7.08	0.9992	200.6	1	12.28	1

(b) $D/T\mu$

WDM (n=6)		FIS (n=3)			
JR	R	100 eV		1 keV	
		JR	R	JR	R
2.74×10^{-4}	0	1.34×10^{-6}	0	2.5×10^{-4}	0

PROBLEMATIQUE du COLLAGE He_μ^+

$$\sigma_{strip}(E) = \sigma^{tr}(E) + \sigma^{ion}(E)$$

sum of charge transfer and ionization with

$$\sigma_n^{tr} = 324n^4(nv)^2/\{[0.187 + (nv)^2][286 + (nv)^7]\}$$

and

$$\sigma_n^{ion} = 5.43n^4(nv)^{16}/\{[1.30 + (nv)^{11.8}][204 + (nv)^{6.2}]\},$$

in $6.55 \times 10^{-22} cm^2$ for muonic atoms for a given bound state n in terms of the He_μ^+ velocity in m.a.u with respect to the in situ D/T ions.

The Jackson-Rafelski ratio (JR) then denotes the probability that the negative muon will be stripped off [1,2] during its slowing down.

It reads as

$$JR = -N_{D/T} \int_0^{3.5MeV} \frac{\sigma_{strip}(E)}{\frac{dE}{dx}} dE,$$

RALENTISSEMENT $He_{\mu}^{+}(35MeV)$ **et** $\mu^{-}(V_0 = 2.19 \times 10^8\text{cm/sec})$

PLASMA WDM $Ne = 5.64 \times 10^{23}/cc$

(a) He_{μ}^{-}

T(eV)	1.75	5	10	15
T_{stop}(psec)	91.57	21.89	9.74	2.59
$R(\mu m)$	513.7	102.43	41.62	3.02

(b) μ^{-}

T(eV)	1.75	5	10	15
T_{stop}(psec)	0.372	0.175	0.0975	0.071
$R(\mu m)$	0.56	0.234	0.12	0.083

PLASMA FIS $Ne = 10^{26}/cc$

(a) He_{μ}^{+}

T(eV)	100	1000
$T_{\rm stop}$(psec)	9.554	0.586
$R(\mu m)$	79.45	3.247

(b) μ^{-}

T(eV)	100	1000
$T_{\rm stop}$(psec)	0.00394	0.0034
$R(\mu m)$	0.0063	0.0053

TRANSITIONS RADIATIVES

Higher levels n ≥ 3 have to be treated with radiative decay down to n=1, included, according to the relationship

$$\Gamma^{\mu}_{rad,if} = M\ \Gamma^{H}_{rad,if}\ ,$$

for a meson of mass M and usual allowed dipole transitions taking place in exoatom (M) or usual H atom, between states i and f. In this regard, it should appreciated that the apparent restriction to $np \rightarrow 1S$ transitions, for exoatom $\frac{D}{T}\mu$,

$$\Gamma^{\mu}_{rad,n1\rightarrow 10} = 206.77 \frac{2^8 n(n-1)^{2n-2}}{(n+1)^{2n+2}} sec^{-1},$$

is not a real one, because the very high Holtzmark field due to the high charge densities, garantees a very efficient Stark mixing of (n,ℓ) sublevels. Transitions are pictured on Table III.

Hydrogenic radiative decay times for exoatom $\frac{T}{D}\mu$ in level n.

n	2	3	4	5	6
τ decay (sec^{-1})	7.75×10^{12}	2.91×10^{11}	7.12×10^{11}	141×10^{10}	2.46×10^{10}

Energie thermonucléaire produite durant le temps de confinement τ

$$Ef = 2\lambda_{\frac{D}{T}\mu\frac{D}{T}} \times Q_{DT} \int_0^{\tau} dt N_{\frac{D}{T}\mu}(t)$$

rapportée au coût de la production des μ

$$R_e = \frac{Ef}{N_\mu(t=0)E_\mu}$$

pris au minimum en fonction du nombre quantique n de l'exoatom $\frac{D}{T}\mu$ et de la contribution dipolaire c

WDM (500 psec)			FIS 100 eV (1 psec)			FIS 1 keV (1psec)		
	c=1	c=.1		c=1	c=.1		c=1	c=.1
n=1	33.1	4.17	n=1	1.87	0.57	n=1	0.83	0.404
n=2	124	17.93	n=2	3.89	2.72	n=2	3.49	2.19
n=3	280	45.4	n=3	17.4	11	n=3	3.90	3.32
n=6	1093	246.35						

SOMMAIRE

- $\pi^- - D^+/T^+$ états liés démontrés en plasmas FIS et WDM (R_2)
- Attachement D^+/T^+ sur exoatomes assurés par recombinaison 3-corps (R_3)
- Diagnostique X des exoatomes
- Les cibles ultra-denses et de courte durée de vie domine l'annihilation pion-nucleon
- Les α_S' produits de fusion ne 'collent' pas le catalyseur $\pi^-(\mu^-)$.

CONCLUSION

La catalyse mesonique apparaît possible dans les plasmas ultradenses.