FAST IGNITION AT VERY HIGH ENERGY

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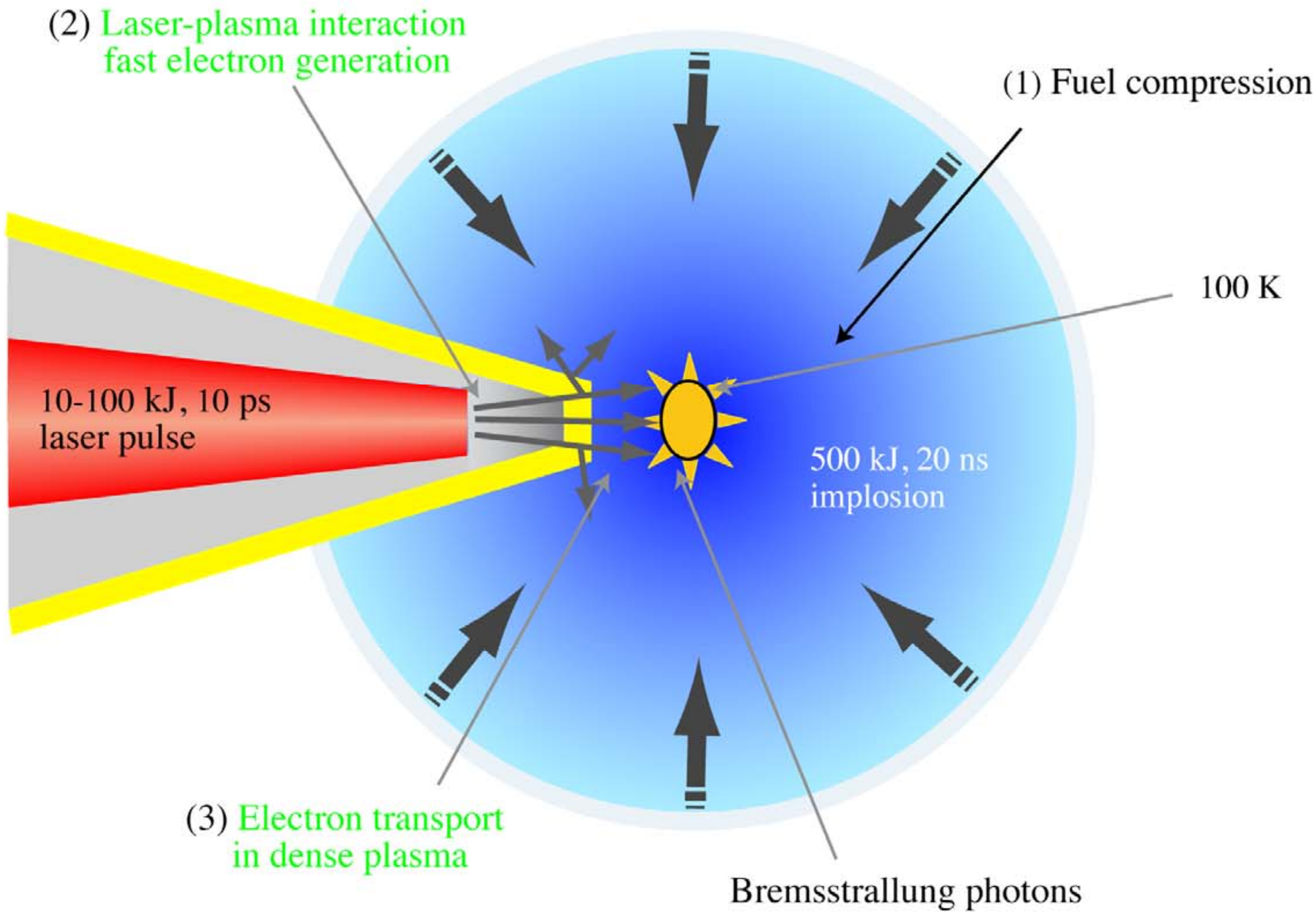
Cone-guided fast ignition with γ-production, through REB-Au interaction



High Z and γ triggered Inelastic Production

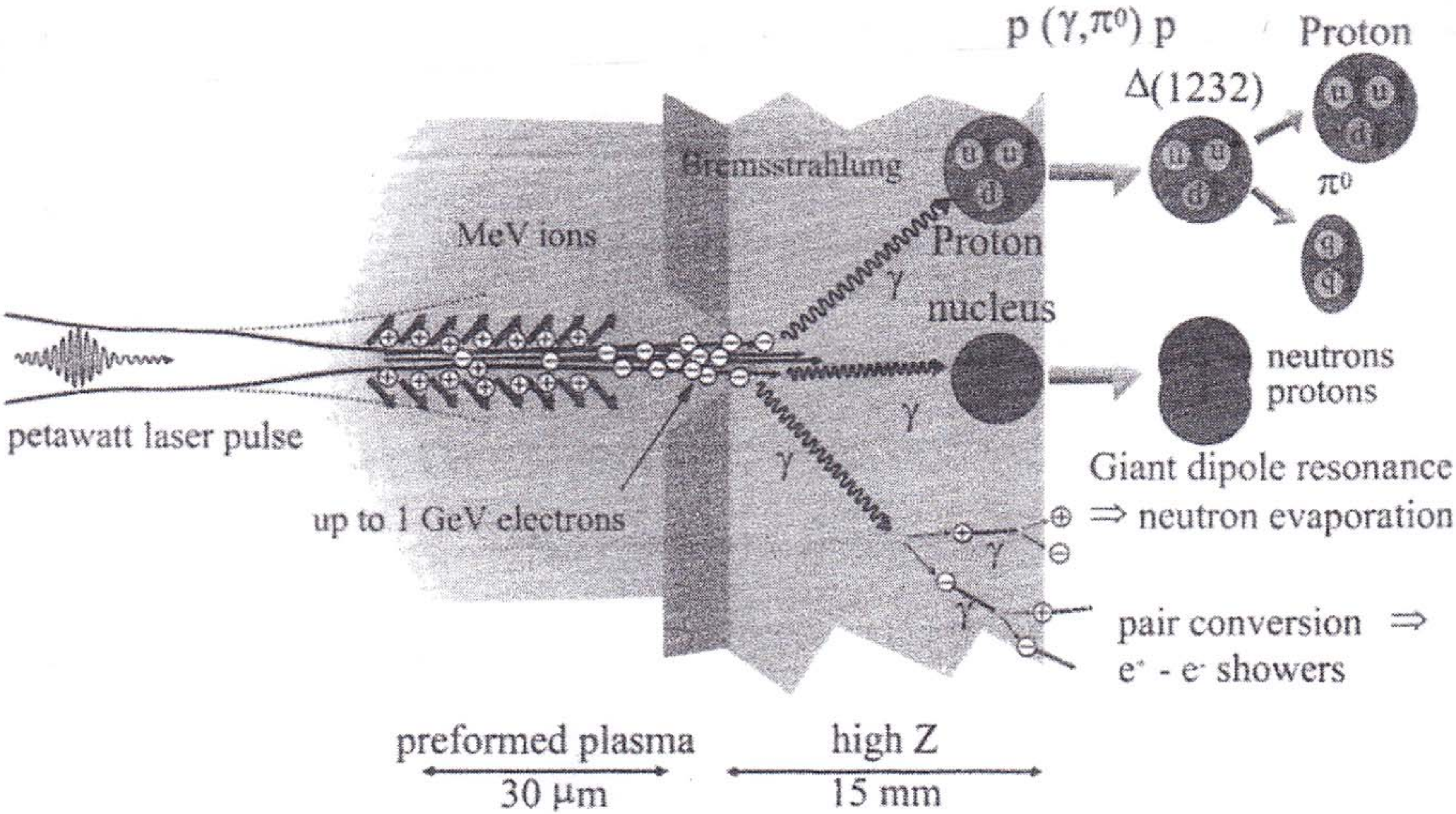


FIGURE 1. Particle production processes triggered by the large electron, ion, and γ fluxes which result from a petawatt laser shot focused into underdense plasma, followed by a solid target. Notice the different scales of plasma and the solid region.

S.Karsch et al LPB 17,565(1999)

HIGH ENERGY REB (γ_b>>1)

- Less initial intensity requested
- Easier 'piercing' through electromagnetic instabilities
- Novel stopping mechanisms available
- Strong Langmuir stopping efficient at $\gamma_b >> 1$
- Huge number of possible collisional stopping channels available

GROWTH RATES OF E.M. INSTAS DECREASE WITH γ_b

In the beam direction, the Two-Stream instability reaches a maximum for $Z_z \sim 1$ with maximum growth rate in ω_p units

$$\delta^{TS} \sim \frac{\sqrt{3}}{2^{4/3}} \frac{\alpha^{1/3}}{\gamma_b}$$

In the direction normal to the beam, the Filamentation instability instability growth rate behaves for small Z_x as

$$\delta^F \sim \sqrt{\frac{\alpha}{\gamma_b}} Z_x \quad , \quad Z_x = \frac{k_x V_p}{\omega_p}$$

and then saturates for $Z_x >> \beta$ at

$$\delta^F \sim \sqrt{\frac{\alpha}{\gamma_b}}.$$

Absolute maximum growth rate for oblique wave vector with $Z_z \sim 1$ and $Z_x >> 1$. Maximum Two-Stream/Filamentation growth rate

$$\delta^{TSF} \sim \sqrt{\frac{3}{2^{4/3}} \left(\frac{\alpha}{\gamma_b}\right)^{1/3}}.$$

A. BRET et C. DEUTSCH, *PoP* **12**, 82704 (2005)

Strong Langmuir Turbulence

$$\theta = \text{angle}\,(\overrightarrow{REB}, \vec{k})$$

Wr = energy density in L waves resonating/REB
A crude threshold estimate for spectra with the typical

$k \sim \omega_e / c$ is $W_{th} \sim n_e T_e^2 / m_e c^2$.

Local REB relaxation length in turbulence is

$$L_r \sim (c / 2\omega_e)(m_e c^2 / T_e)^2 (\gamma_b \Delta\theta)^2 (W_{th} / W_r).$$

For $\omega_e \sim 6 \times 10^{17}\,\text{sec}^{-1}$ and $T_e \sim 5\text{keV}$, this simplifies to

$$L_r \sim 2.5(\gamma_b \Delta\theta)^2 (W_{th} / W_r)\ \mu\text{m}.$$

If $W_r > W_{th}$, this length would not exceed 50 μm for $\gamma_b \Delta\theta \leq 5$.

V M Malkin and N J Fisch PRL89,125004(2002)
T Yabuuchi et al New J Phys 11,093031(2009)

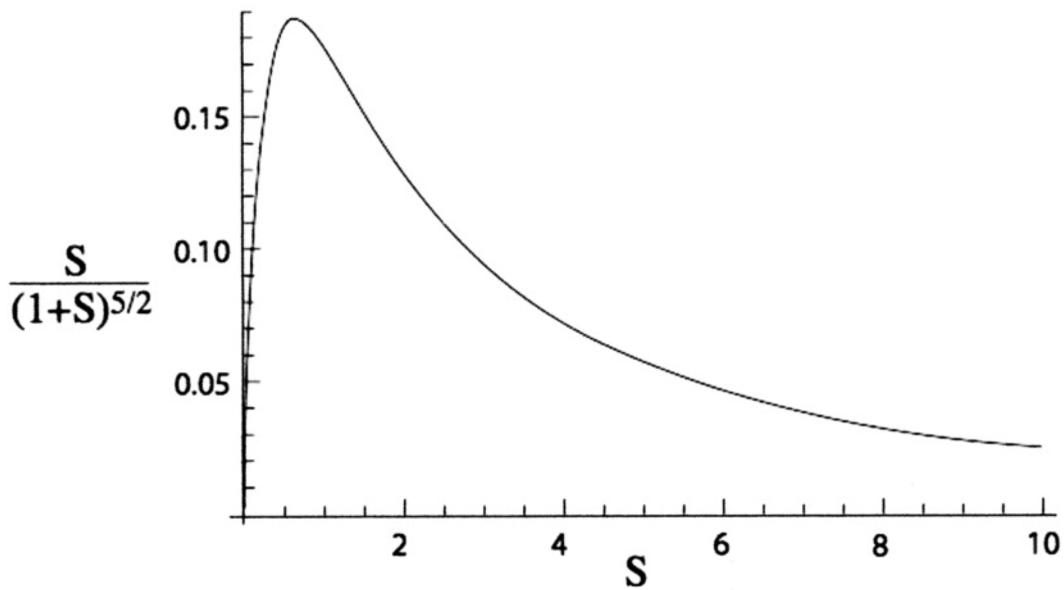
REB STOPPING THROUGH 2-STREAM INSTABILITY

Based upon a single wave approximation in which the wave is assumed to reach its maximum amplitude instantaneously, a semi quantitative analytic solution for the fraction of beam energy converted into electric field energy is predicted to be

$W \equiv |E|^2 / 16\pi n_b \gamma_b mc^2 = 0.5 \;\; S(1+S)^{-5/2} \sim 10\%$ of initial beam energy at Eb~MeV

where $\beta_b \gamma_b (n_b / 2n_p)^{1/3}$ is the strength parameter and $\gamma_b = v_b / c$

cf L.E. Thode. Phys. Fluids **19**, 305 (1075)



$$\text{Maximum at } E_b = 15 \text{ MeV for } \frac{n_b}{n_p} \sim 10^{-4}$$

$$\text{Maximum at } E_b = 200 \text{ MeV for } \frac{n_b}{n_p} \leq 10^{-7}$$

REB STOPPING THROUGH SHOCK IN INHOMOGENEOUS PLASMA

cf S.K Yadav *et al.* POP **16,** 040701 (2009)

- 2D EMHD

- Net Energy Dissipation Rate over Length L

$$Q \sim KLb^2a^2V_b$$

$$= \frac{B^2}{4\pi}\pi a^2 V_b = I^2 \frac{V_b}{c^2} = R \ I^2$$

with

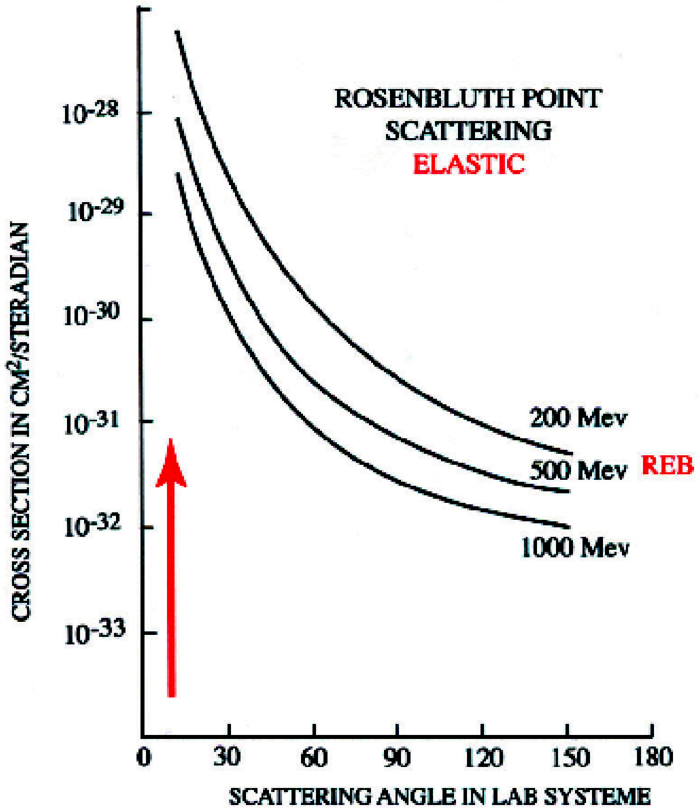
k = inverse of normalized density scale length

b = normalized B in x -z plane

a = channel dimension

I = 300 kA at E_b = 10 MeV can thus get stopped

REB Stopping on Target Ions



Rosenbluth-point scattering for point-protons with real values of nuclear spin and magnetique moment. The appropriate cross section is given with K = 1.79 nuclear magnetons, $\mu_p = 2.79$ n.m. by

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \left(\frac{e^2}{2E_0}\right)^2 \frac{\cos^2\theta/2}{\sin^4\theta/2} \frac{1}{1+\frac{2E_0}{Mc^2}\sin^2\theta/2}$$

$$\left\{1+\frac{\hbar^2 q^2}{4M^2c^2}\left[2(1+K)^2\tan^2\theta/2+K^2\right]\right\}$$

$$(\mu p = 1 + K = 2.79 \text{ n.m.})$$

REB STOPPING ON TARGET ELECTRONS

The following expression has been obtained as a careful pseudoanalytic fit to quantum stopping results. It is essentially accurate for n_e Š 10^{26} e-cm^{-3}, as evidenced from stopping data.

$$-\frac{dE_b}{dx} = \frac{4\pi n e^4}{mv^2}\,\mathrm{In}\left(\frac{2mc^2\gamma_b^2}{\hbar\omega_p}\right)$$

K Starikov and C. Deutsch, PRE 71, 026407 (2005)

Equivalent section efficace (cross section)

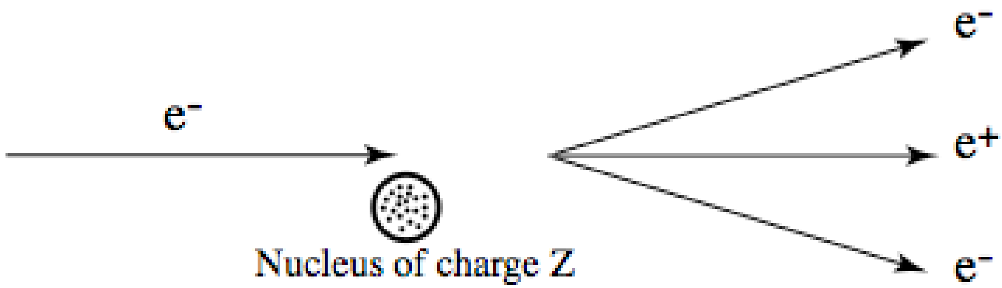
$$-\frac{dE_b}{dx}\left(\frac{\mathrm{MeV}}{\mathrm{cm}}\right) = n * E_b * 2.5\times10^{-25}\,\mathrm{cm}^{+2}$$

equivalent σ

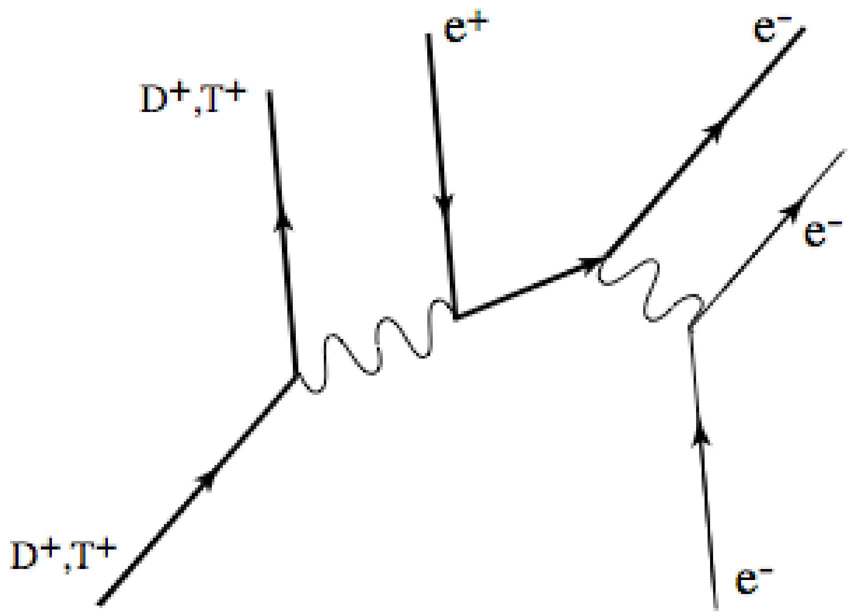
100 times Trident process for E_b = 200 MeV.

→ R(μm) = 259 at 15 Mev

24 at 1 MeV

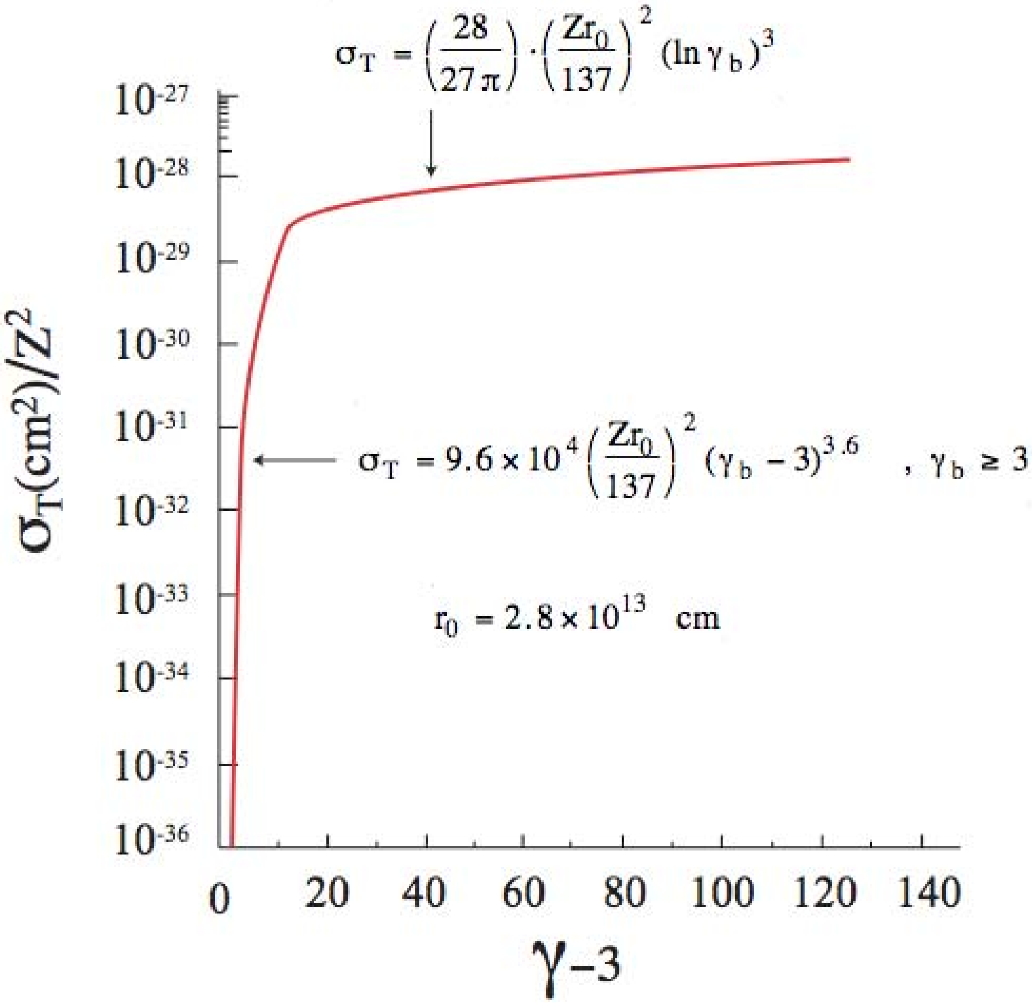


Schematic of trident process of pair creation



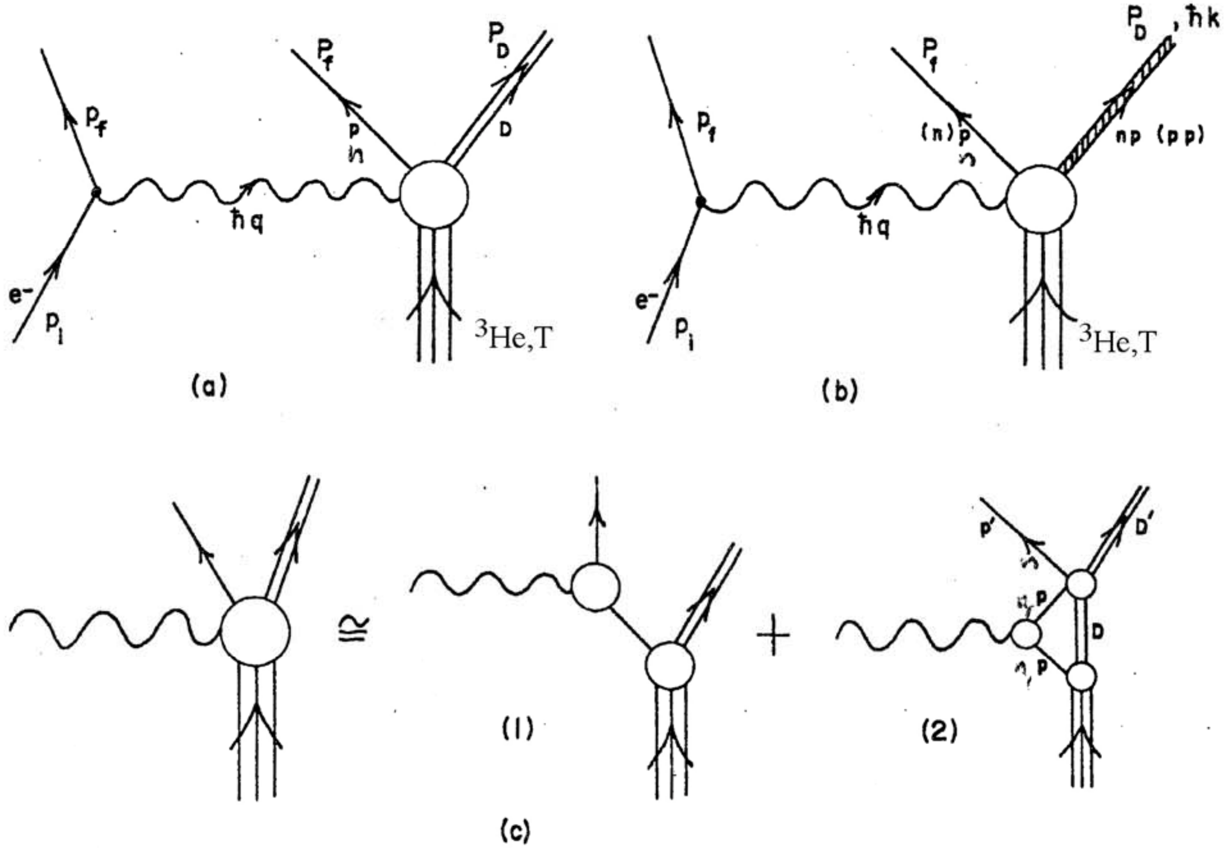
A Feynman graph contributing to Trident production

$$e + {}^{D}_{T} \longrightarrow e + e + \bar{e} + {}^{D}_{T}$$



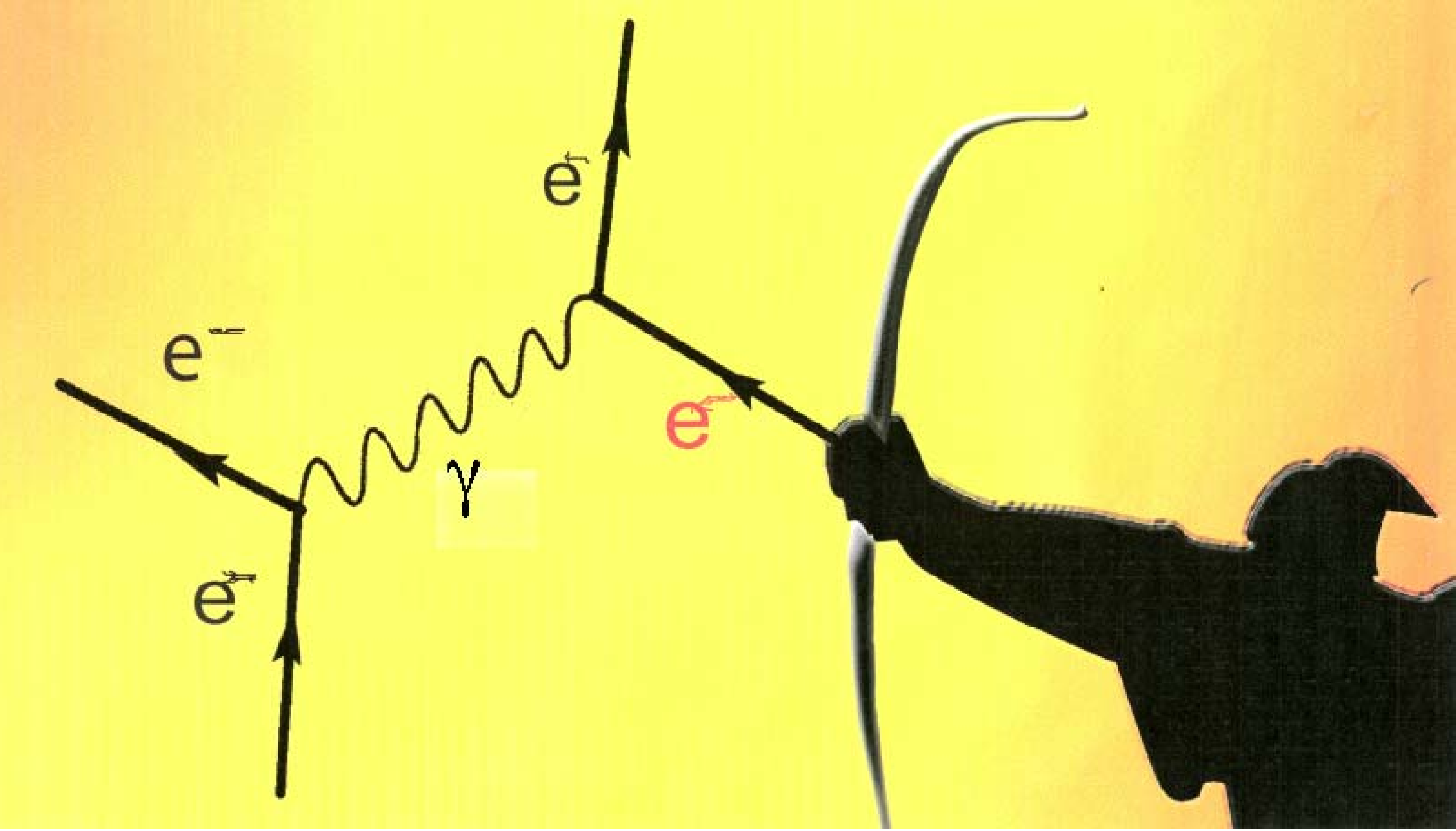
Total cross section σ_T of the trident process plotted vs the dimensionless electron-energy excess above the threshold. Here $\gamma = E/m_0c^2$.

Quasielastic Electron Scattering from ^{3}He and ^{3}H

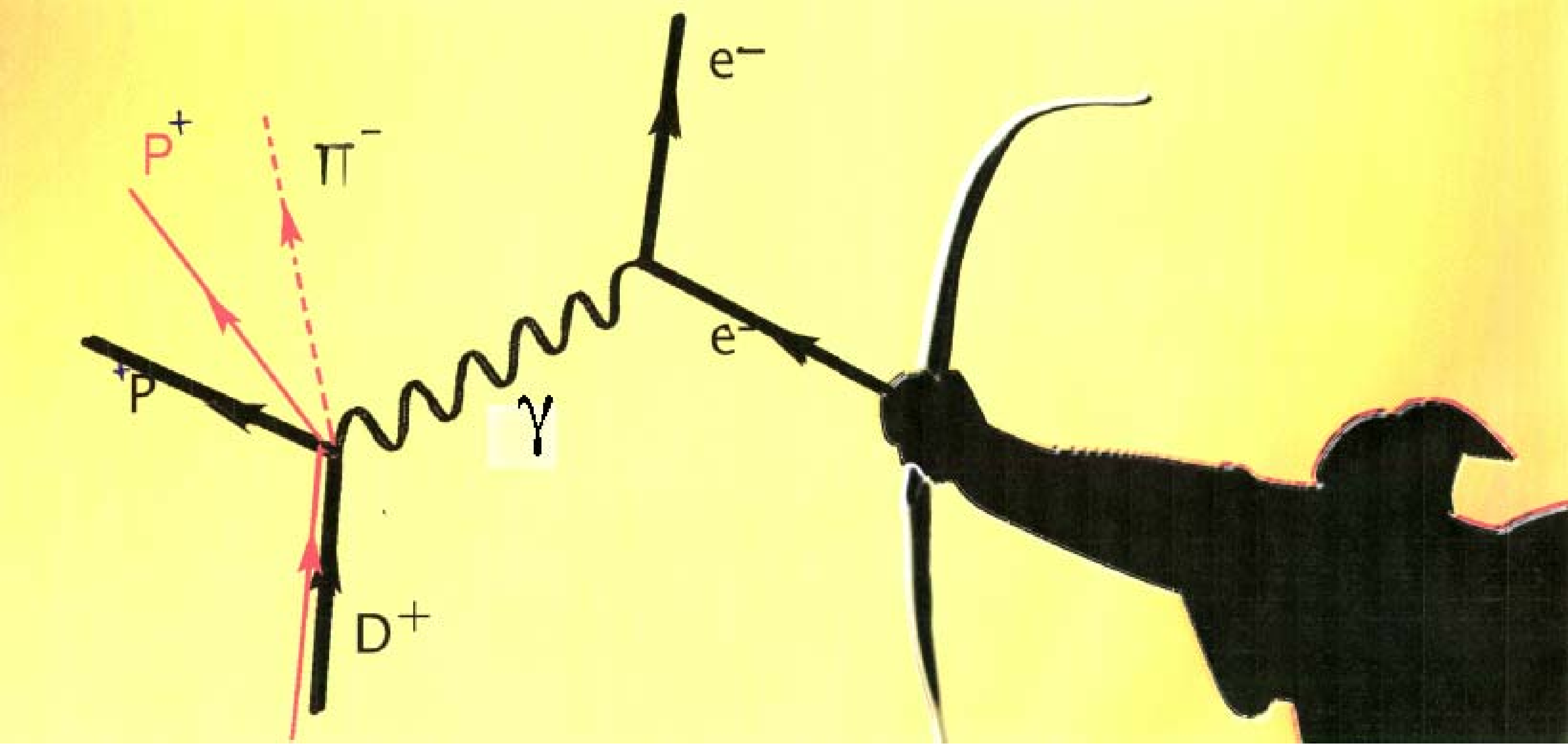


Typical graphs in electrodisintegration of ^{3}He, T, (a) and (b) show the one-photon-exchange two- and three-body breakup of ^{3}He, T, (c) shows the decomposition of the p-D-^{3}He nuclear vertex into the proton pole (1) and a correction to the proton pole (2). All intermediate states are on the mass shell.

Möller Diagram

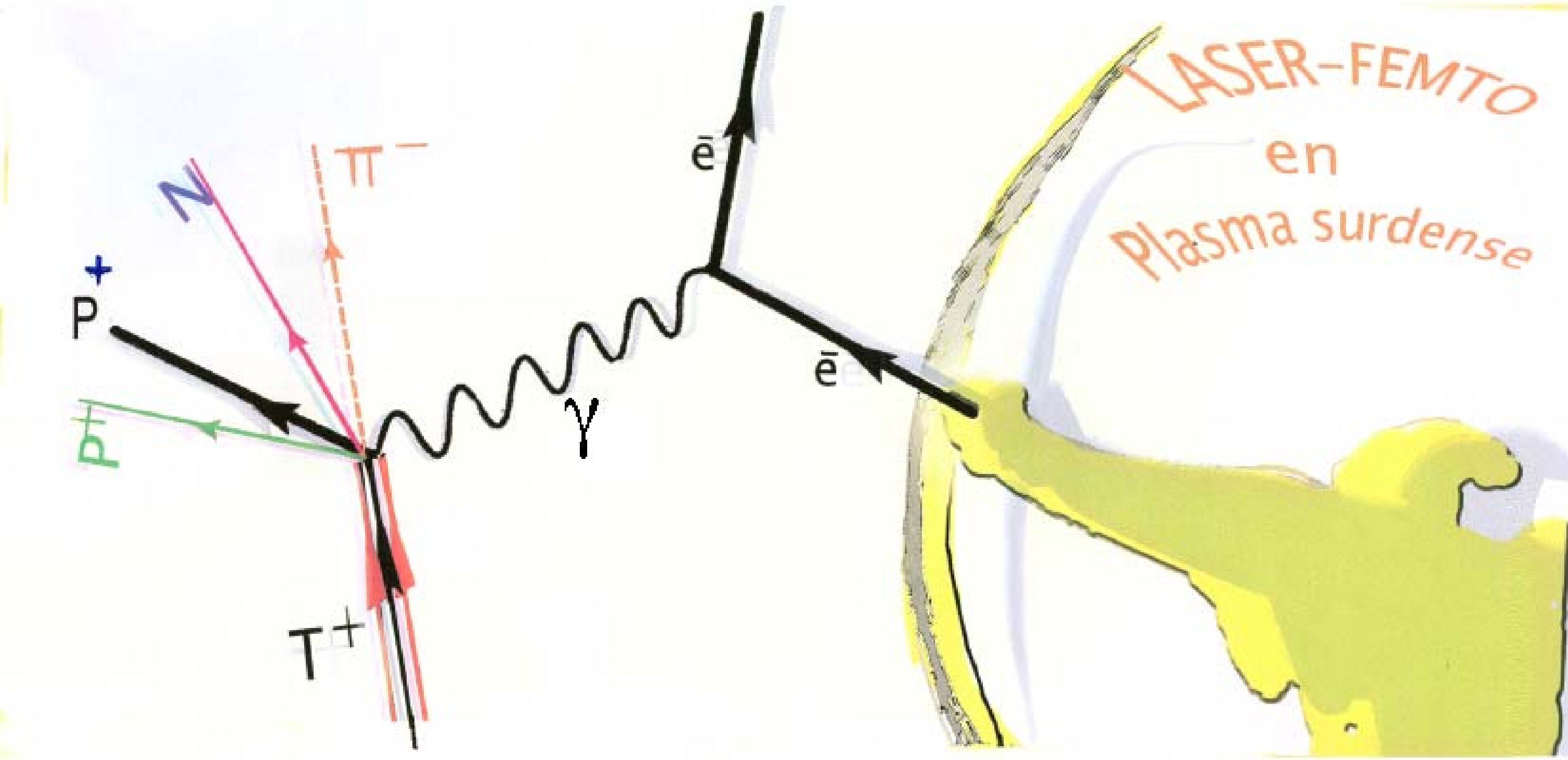


D^+ Electro disintregation



One virtual Gamma only up to 1 GeV

T^+ Electro-Disintregation



nS-state pion capture fractions in hydrogen

M. Leon and H.A. Bethe, *Phys. Rev.* **127**, 636 (1962)

Capture on level $n \sim (M_\pi/M_e)^{1/2} \sim 16$ and cascade down $\rightarrow n = 1$

Principal quantum number nS-state capture fraction

n	
7	0.003
6	0.013
5	0.09
4	0.44
3	0.39
2	0.04

REB-Hard Gamma Conversion

- Cone target allows for electro as well as

DT fuel <u>disintegration</u>

Hard Gammas easily secured through REB bremsstrahlung in gold with

$dE/dx)_{rad}/dE/dx)_{coll} = E_{REB}\ Z/1600\ mc^2$

$= 1 \rightarrow E_{REB} = 10.35$ MeV in Au

$\searrow E_{REB} = 817.16$ in Z =1 DT

CONTRIBUTION TO D- and T – PHOTO DISINTEGRATION THROUGH

REB-BREMSSTRAHLUNG IN Au (Z = 79)

$$Z^2 n_i = \frac{Z^2 \rho N_A}{A} \sim 3.66 \times 10^{26}\, e - cm^{-3} \# Z^2 n_e \sim 10^{26}\, e - cm^{-3}$$

$$\frac{\sigma_T}{\sigma_{\gamma \to e^+ e^-}} = \frac{\alpha}{\pi}\left[\log\left(\frac{E_0}{m_e c^2}\right)\log\left(\frac{E_0}{2.137 m_e c^2 Z^{-1/3}}\right) + \frac{1}{3}\log^2(2.137\ \ Z^{-1/3})\right],$$

$$= 0.017 \ \text{ at } \ 5\ \text{MeV}$$

H.J. Bhabba, Proc. R. Soc. London **A 152**, 559 (1935), cf. J Myatt *et al*. POP **79**, 066409 (2009).

π^- Catalyzed Fusion in FIS Conditions

- π^- production Cost ~150 MeV << 5.2-8 GeV in cold μ CF
- $\sigma_{\pi\text{-}N}$ (a ~ -0.036 fm) << $\sigma_{N\text{-}N}$ (a ≥ 1-8 fm)

$$\Downarrow$$

- Catalytic cycle Mostly electromagnetic
- π-D, π-T ground state hadronically shifted only by 0.022 percent!!
- Cycling rate (n_e ~ 10^{26} e-cm^{-3}) ≥ 10^3 cold cycling rate (n_{LHD} ~ 4.25×10^{22} e-cm^{-3})
- Reduced final pion alpha sticking in hot, dense plasma.

Relevant lengths

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

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

Debye length ~ $2.35\text{x}10^{-9}$ cm

Bohr radius (electron) = 5.29 x 10^{-9} cm.

Bohr radius (pion) = 1.94 x 10^{-11} cm

π-D and π-T atoms hardly affected

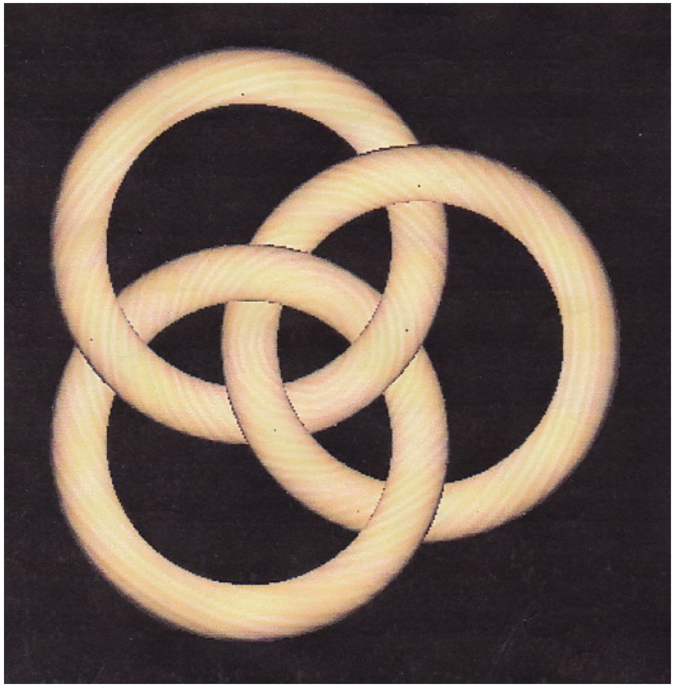
by electron Debye-screening.

Considering an ignition plasma (N~10^{26}/cc, T~3-5 KeV)in a Debye approximation demonstrates a persistence of pionic molecular ions pi-D+T+ with 319.13 eV binding energy for vibrational number V= 0 and total angular momentum number J = 0, wrt to D^+-π^- and T^+-π^-. Such bound systems are equivalent to excited atoms with main quantum number N = 12 and exhibiting anisotropy due to a nearby D+ or T+ion.

N = 12 remains out of immediate nuclear capture

BORROMEAN STABLE CONFIGURATIONS

DT_{π}, DD_{π}, TT_{π}, $DT_{\pi\pi}$, $DD_{\pi\pi}$, $T_{\pi\pi}$,



Let us number the particles in such a way that the following inequalities are valid for their masses:

$$m_1 \geq m_2, \quad m_3 \geq m_4, \quad m_2 \geq m_4.$$

With this numbering of particles the lowest dissociation threshold for the four-particle system, E_{th}, in the system of Hartree atomic units ($\hbar = 1$, $m_e = 1$, $q_e = 1$) is

$$E_{th}(m_1^+ m_2^+ m_3^- m_4^-)$$

$$= -\frac{m_1 m_3}{2(m_1 + m_3)} - \frac{m_2 m_4}{2(m_2 + m_4)}$$

while the lowest dissociation (ionization) threshold for the three-particle system is

$$E_{th}(m_1^+ m_2^+ m_3^-) = -\frac{m_1 m_3}{2(m_1 + m_3)}$$

$$s = \left(\frac{1}{m_1} + \frac{1}{m_3}\right) \Big/ \left(\frac{1}{m_2} + \frac{1}{m_4}\right)$$

$0.4710 \leq s \leq 2.1231$ Stable

BORROMEAN CONFIGURATIONS

$T^{+}D^{+}\pi^{-}e^{-}$ system (s = 0.0007) unstable

In these Borromean schemes, DT_{π}, $DT_{\pi\pi}$ . . . with $s \cong 1$ are stable. This system can bind one more electron forming $(M^{\mp},M^{+},x^{-},e^{-},e^{-})$, which is akin to H^{-}. A possible choice of x^{-} is π^{-}. The (p,p,π^{-}) system is bound, and the (p,p,e^{+},π^{-}) and $(p,p,e^{-},e^{-}\pi^{-})$ systems are also bound. These systems remain bound even if the masses of the heavy particles are slightly different, e.g., the $(M_1^{+},M_2^{+},e^{-},e^{-},x^{-})$ system is bound as a rough estimate for $1/3 < M_1/M_2 < 1$.

$$\uparrow$$

$$\frac{m_D}{m_T} \sim 2/3$$

In a mostly electron-screened target, mesomolecules appear nearly Coulombian

DEBYE-SCREENED MOLECULES

$$V(r_a, r_b) = q_a q_b \exp\frac{(-|r_a - r_b|)}{D} / |r_a - r_b| \ .$$

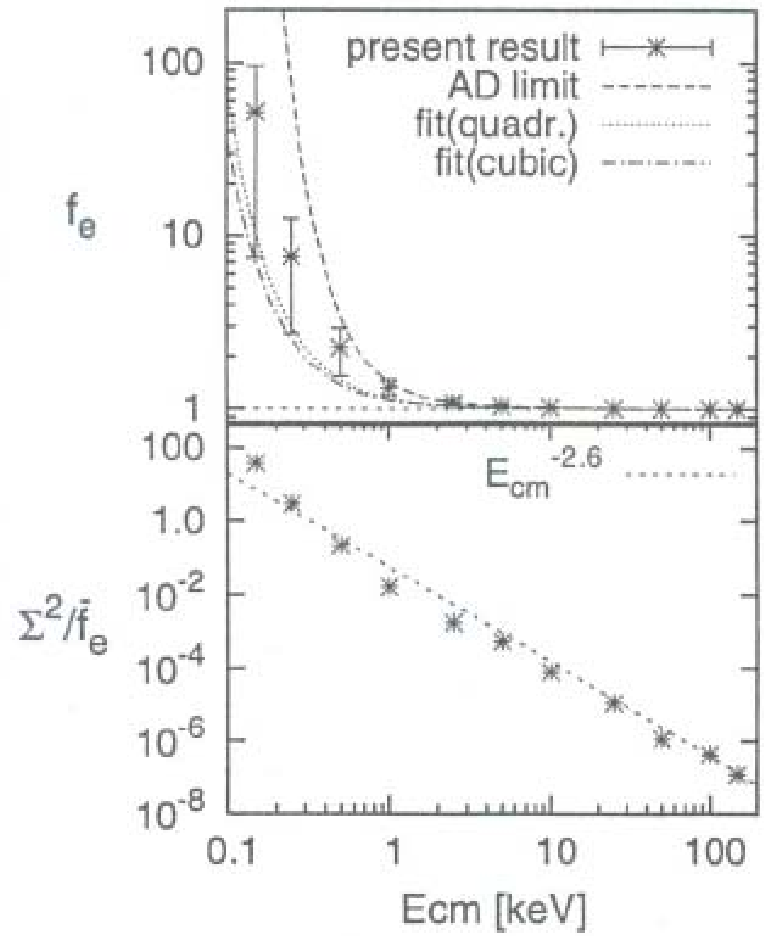
$$H = -\frac{1}{2m_1}\nabla_1 - \frac{1}{2m_2}\nabla_2 - \frac{1}{2m_3}\nabla_3 + V(r_3, r_1) + V(r_3, r_2) + V(r_2, r_1) \ ,$$

Ground and excited states energies of plasma-embedded td_μ molecular ion for different screening parameter along with the n = 1 threshold energies of tμ. Quoted results are in m.a.u.

D	tμ (n= 1)	tdμ (J=0, v = 0)	tdμ (J=0, v = 1)
∞	- 0.481874166748	-0.538594975	-0.488065358
100	- 0.471951457103	-0.528664171	-0.478140323
50	-0.462181262989	-0.518869867	-0.468363045
30	-0.449386465096	-0.506018492	-0.455551309
20	-0.433756779919	-0.490279822	-0.439888656
15	-0.418520153061	-0.474893060	-0.424606668
10	-0.389182419992	-0.445137640	-0.395145273
8	-0.368133808415	-0.423678964	-0.373979717
6	-0.334783387306	-0.389475264	-0.340399609
5	-0.309590742305	-0.363459345	-0.315000779
4	-0.274153085855	-0.326575303	-0.279231352
3	-0.220971475522	-0.270488395	-0.225474576
2.5	-0.183360941776	-0.230169921	-0.187411245
2.0	-0.134547882290	-0.176754630	-0.137964289
1.5	-0.071690979839	-0.105039966	-0.074215725
1.2	-0.029655544877	-0.052965468	-0.03145845
1.1	-0.0168475687	-0.035286667	-0.0183319
1.0	-0.00634745	-0.018756598	-0.00739
0.9	-0.000378	-0.0053050	-0.00046
0.89	-0.00016	-0.0042584	

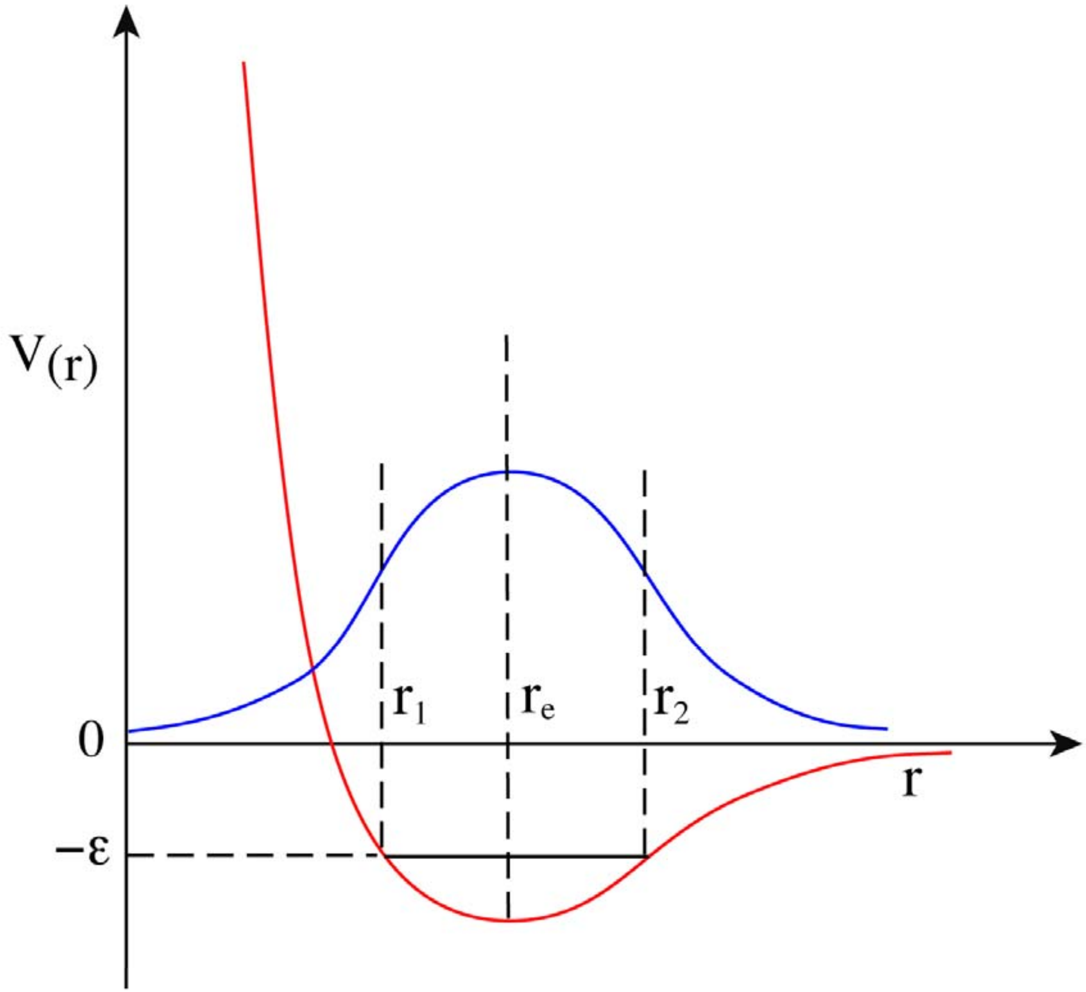
Larger systems are better armed to survive screening

Chaotic Nuclei Screening   Coulomb Barrier Lowered by 2 Orders of Magnitude

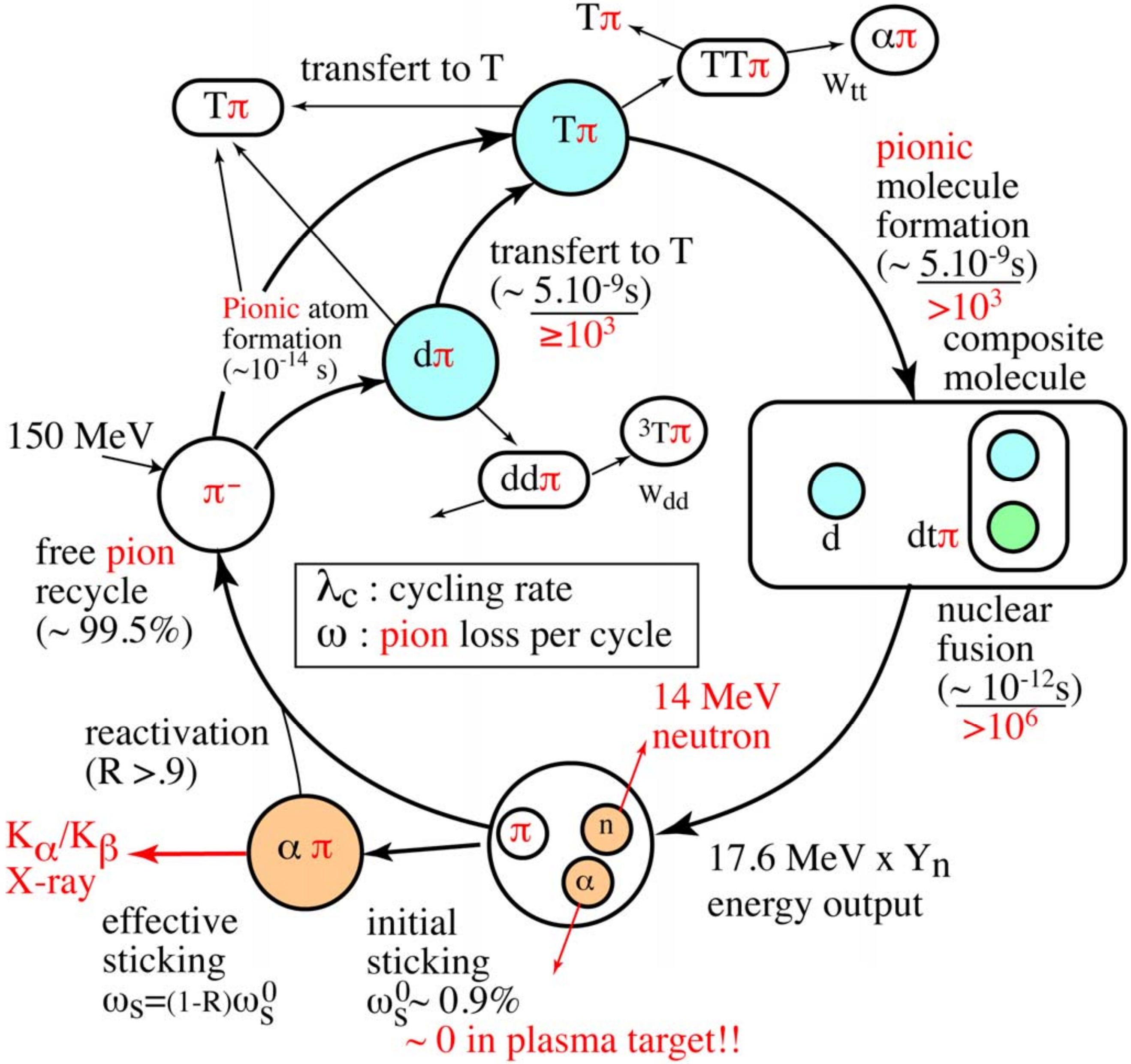


Enhancement factor as a function of incident center-of-mass energy for the D + d reaction (upper panel). The corresponding $\Sigma^2/\bar{f}_e$ (stars) and a power-law fit (dashed line) (lower panel).

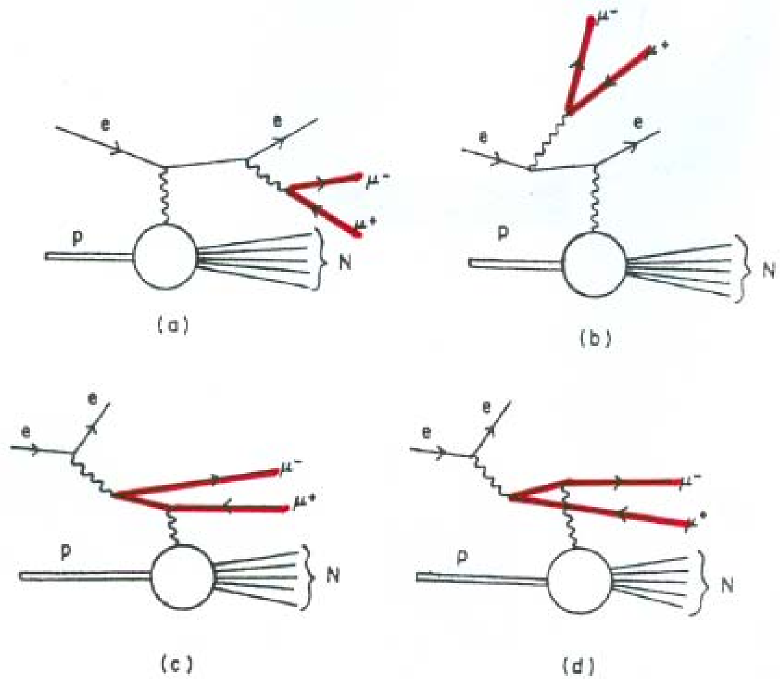
S. Kimura, A. Bonasera, PRL. 93.262502 (2004)



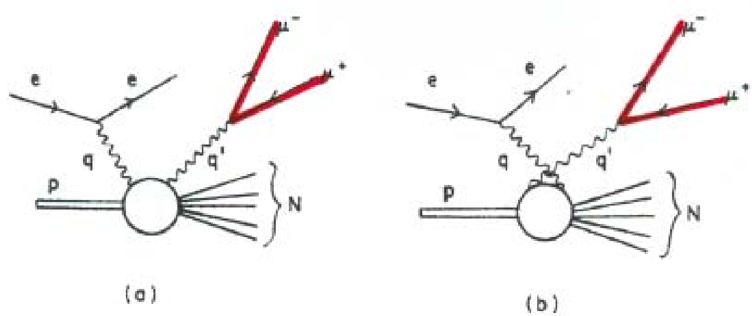
Nuclear potential energy curve in π-mesonic hydrogenic molecule, and ground-state vibrational wave function for the while r_1 and r_2 are the classical turning points. The bound state energy level is -ε.



Possible diagram of the pion catalyzed fusion cycle
in FIS conditions



Lowest-order Bethe-Heitler-type diagrams contributing to the process $e+p \rightarrow e+\mu^- + \mu^+ +$ "anything." The contribution of such diagrams to the cross section can be calculated in terms of structure functions W_1 and W_2.



Lowest-order Compton-type diagrams contributing to the process $e+p \rightarrow e+\mu^- + \mu^+ +$ "anything."

PROVISIONAL SUMMARIES

- Strong Langmuir turbulence and inelastic high energy REB offer new prospects for FIS/ICF.
- Pion catalyzed fusion could provide substantial contributions: cheaper, faster and No sticking.
- Discontinuous REB stopping through γ-and (e^+-e^-) pair productions remain to be explored.
- π^- stopping needs more investigation.

Production of Borromean molecular states via (e-e+) decay into Wheeler complexes ne-me+ and Pi- catalysis out of DT electro and photodisintegration (cone target)