Fusion Rate Formulas for Bosonized Condensates

Akito Takahashi

First Presented at Tutorial Class
Of ICCF12, 27 Nov. 2005
(Revised on 10 April 2006)

Aim

- Clean Fusion and Cold Transmutation in Condensed Matter are theorized by Bosonized Condensates Models.
- Formulas for Reaction Rates and related QM derivations are summarized.
- Some numerical results are shown for EQPET/TSC models.

Major Experiments

(green; after 2001)

1) Excess Heat with He-4

Miles, Arata, McKubre, Gozzi, Isobe, de Ninno
Celani, El Boher, and so on

2) Cold Transmutations

Iwamura, Mizuno, Miley, Ohmori, Celani, Karabut
Szpak, and so on

3) Weak Neutron Emission

Jones, Takahashi, Mizuno and so on

4) Anomalous DD Enhancement

Kitamura, Kasagi, Takahashi, Huke and so on

[Essential Conclusions of Recent Studies]:

① Clean Fusion Phenomena producing ^{4}He ash and energy

② Occurrence of Cold Transmutation and Fission

③ Consistent Theoretical Models for Condensed Matter Nuclear Effects

3. Theoretical Studies on CMNE

- Since 1989, more than 150 models proposed in the world
- NO ESTABLISHED THEORIES, so far
- **SOME HOPE for Nuclear Reactions Models under Ordering Environments in Metal/D or Metal/H CM-Systems**

3.1 Nuclear Fusion Reactions in CM （Strong Interaction）:

D-Cluster Fusion Models:
EQPET/TSC(Takahashi), EODD(Kirkinskii),
Bose-Einstein Condensation Models:
Kim, Tsuchiya
Resonance Tunneling:
X.Z. Li
Phonon-coupled gauge theory:
Hagelstein
Coherent Bloch-state Models:
S. Chubb, T. Cubb
Swimming electron layer model:
Hora-Miley
SCS Fission Model:
Takahashi-Ohta

In CM-Systems- Solid-State-Physics-;
How Constraint/Ordering of Particles (d/p)
can play role in New Nuclear Reaction Process?
Overcome Coulomb Barrier,
Route to New Reaction Channel
Quantitative and Qualitative Consequences

Especially, Quantitative Predictability is KEY!
How can it correspond to Experimental Rate Level?

（**D+D → ^{4}He + lattice-energy(23.8MeV)**
is not possible
In Nuclear Physics View Point）

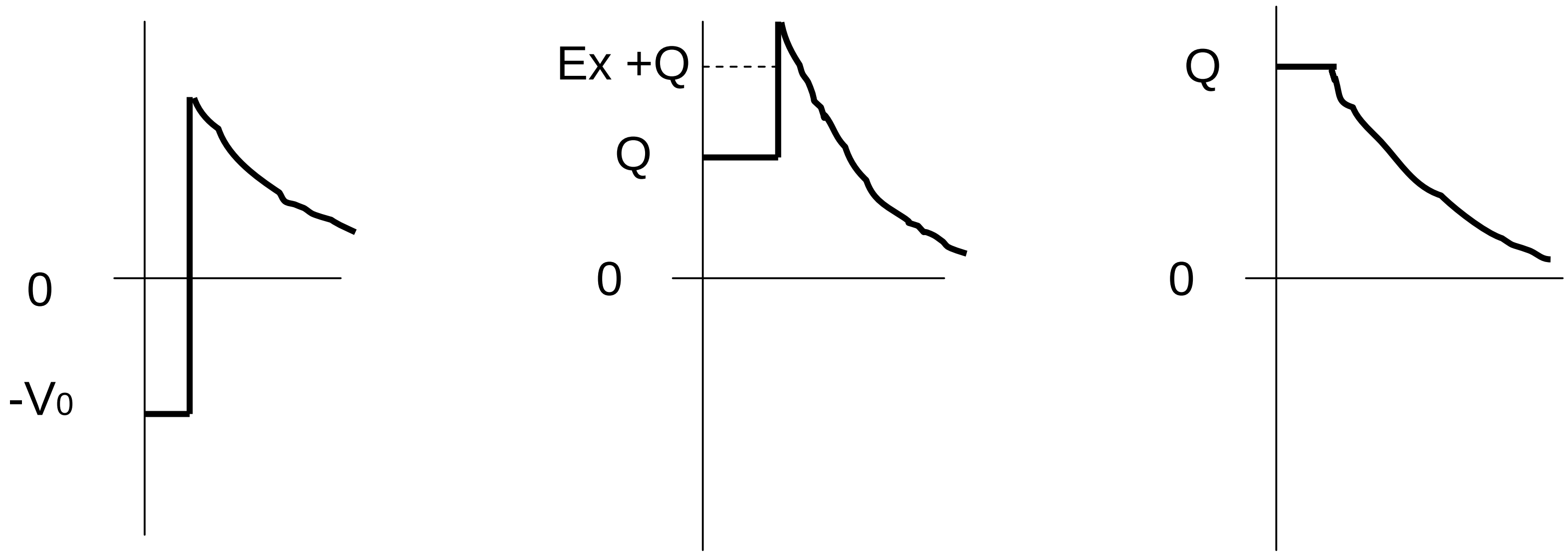
Trend：Nuclear Fusion Models under Ordering Processes In/0n CM

- Coherent Fusion Models：Hagelstein, Chub-Chub, Li, Violante, etc.,
- Cluster Fusion (TSC) models： Takahashi, Kirkinskii, Tsuchiya, etc.
- Clean Fission Models：Takahashi-Ohta, Karabut

Part-I: Basic Theory

- Strong Interaction
- Global Optical Potential and Fusion
- QM Density Flow and Mean free Path
- Adiabatic Potential for dde*
- Fusion Rate Formulas

Three Potentials for Nuclear States

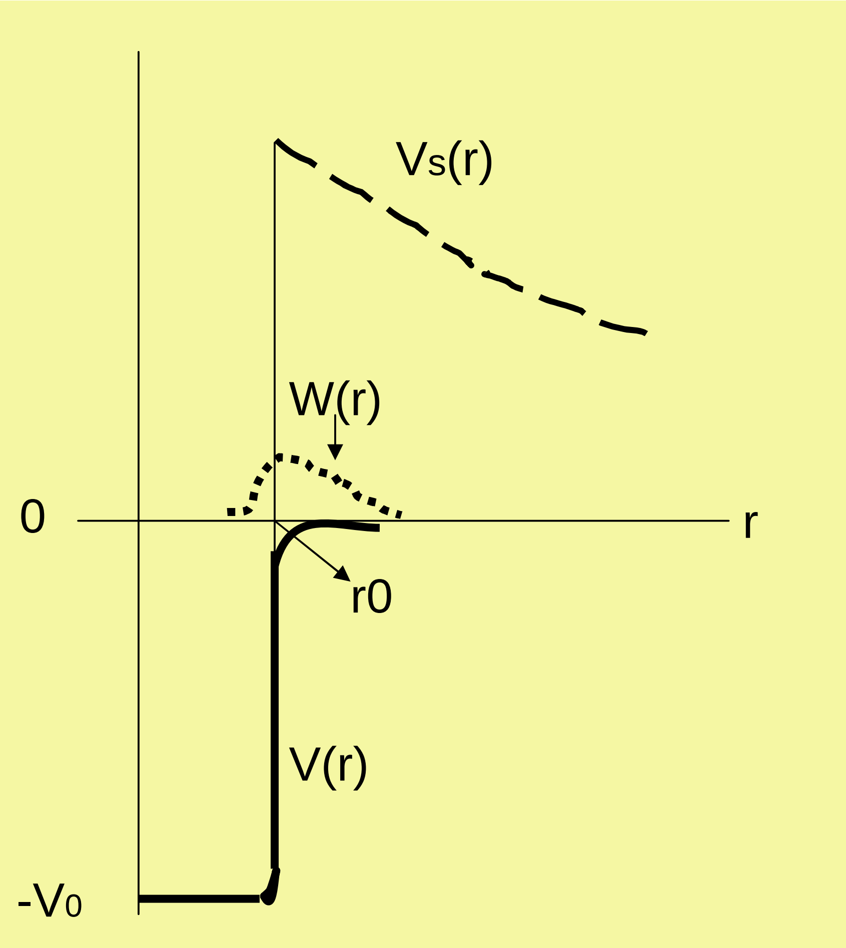


(I) Stable:
Stable Isotopes
A < 60

(II) "Meta" Stable:
Stable Isotopes A>60
Radio-active states

(III)
Spontaneous
Break-up

Optical Potential for Strong Interaction



- **U(r) = V(r) + iW(r)**
- V(r) ~ -25 to -50 MeV
- W(r) ~ 0.1 to 5 MeV
- For fusion by surface sticking force:

  $W(r) \sim W_0 \, \delta \, (r - r0)$

- $V_s(r)$: screened Coulomb potential

Scattering Amplitude $f(\theta)$

- Asymptotic wave after scattering:

$\Psi(r) \sim e^{ikz} + f(\theta)(e^{ikr}/r)$

- Differential Cross Section:

$(d\sigma/d\Omega) = |f(\theta)|^2$

- S-matrix elements: S_ℓ

$$f(\theta) = (1/2ik)\sum_{\ell=0}^{\infty}(2\ell+1)(S_\ell - 1) P_\ell(\cos\theta)$$

$S_\ell = \exp(2i\delta_\ell)$

by Phase-Shift Analysis (Elastic Scattering)

T-Matrix

- For **transition from $\alpha\beta$ to $\alpha'\beta'$ channel**;

$f(\theta;\alpha\beta \text{ to } \alpha'\beta') =$

$$-(2\pi\mu/h^2)\langle \Psi_{\alpha'\beta'} | T | \Psi_{\alpha\beta} \rangle$$

- Lippmann-Schwinger equation:

$T = U + UG_0T$

$G_0 = (E - H_0 + i\delta)^{-1}$; Green function

$H = U + H_0$

- If we set T=U, Born Approximation

Reaction Cross Section

$$\sigma_{r,0} = \pi ƛ^2 \frac{-4kR \operatorname{Im} f_0}{(\operatorname{Re} f_0)^2 + (\operatorname{Im} f_0 - kR)^2}$$

$$f_0 = KR \cot KR$$

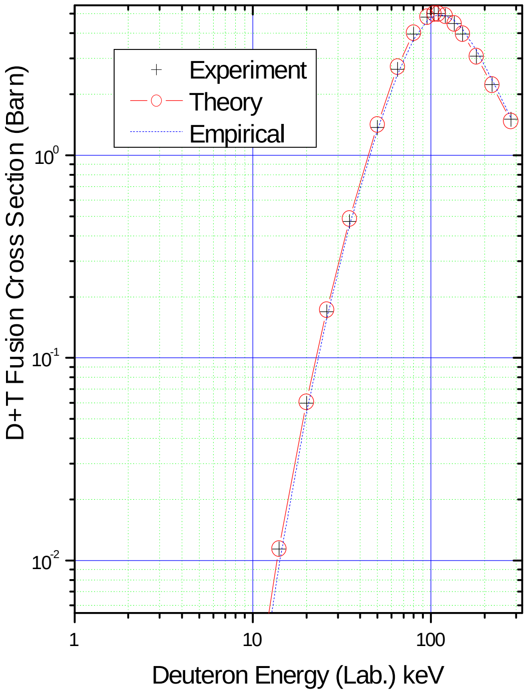
$$K = \frac{1}{\hbar}\sqrt{2M(E + V + iW)}$$

$$T_\ell = e^{i\delta_\ell} \sin \delta_\ell$$

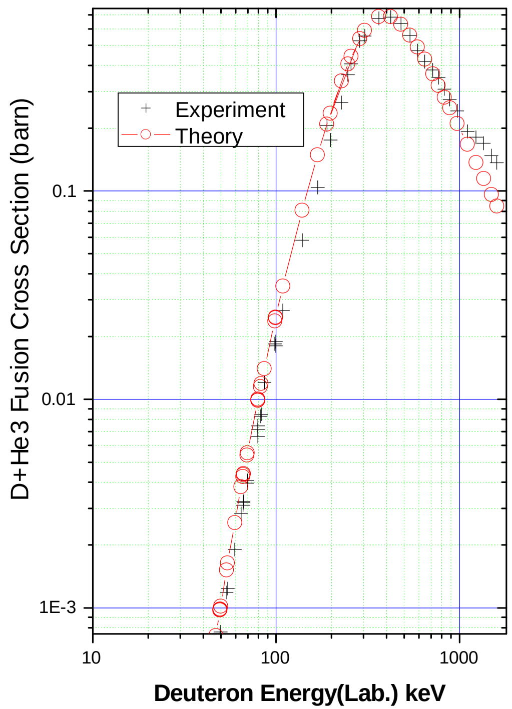
$$S_\ell = 1 + 2iT_\ell$$

X.Z. Li: ICCF11

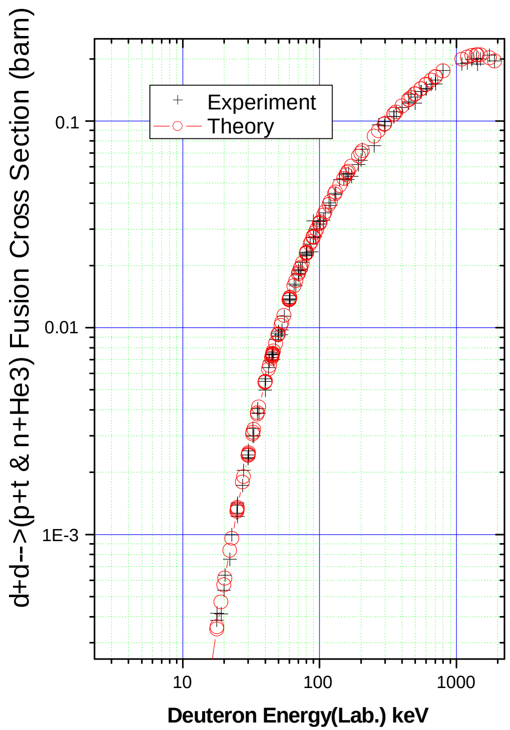
Selective Resonant Tunneling ○ & NNDC Data +



D+T



D+He3



D+D

X. Z. Li, H.Hora, et al., *Laser and Particle Beam*, 22 No.4 (2004)

Li: ICCF11

$$S_0 = e^{i2\delta_0} \qquad Cot(\delta_0) = W_r + iW_i$$

$$\sigma_r^{(0)} \approx \frac{\pi}{k^2}(1-|S_0|^2) \equiv \frac{\pi}{k^2}\left\{\frac{-4W_i}{W_r^2+(W_i-1)^2}\right\}$$

Reaction Cross Section

$$\begin{cases} W_r = 0 \\ W_i = O(-1) \end{cases}$$

$$\begin{cases} E = 110\ \mathrm{keV} \\ \sigma_r^{(0)} = 5.01\ \mathrm{b} \end{cases} \qquad \begin{cases} U_{1r} = -47.33\ MeV \\ U_{1i} = -115.25\ keV \end{cases}$$

$$a = 1.746\times 10^{-13}(A_1^{1/3} + A_2^{1/3})\ cm$$

Text Books for Phase-shift Analysis

- L. I. Schiff: Quantum Mechanics, Chapter V, McGraw Hill, 1955

- J. M. Blatt, V. F. Weisskopf: **Theoretical Nuclear Physics**, Chapter VIII, Springer-Verlag, 1979

Mean Free Path in Strong Field (1)

- Forward Equation:

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2M}\nabla^2 + V + iW \right]\Psi \qquad (1)$$

- Adjoint Equation:

$$-i\hbar \frac{\partial \Psi^*}{\partial t} = \left[-\frac{\hbar^2}{2M}\nabla^2 + V - iW \right]\Psi^* \qquad (2)$$

- Ψ*x(1) – Ψ x(2):

$$i\hbar\left(\Psi^* \frac{\partial \Psi}{\partial t} + \Psi \frac{\partial \Psi^*}{\partial t} \right) = i\hbar \frac{\partial \Psi\Psi^*}{\partial t} = i\hbar \frac{\partial \rho}{\partial t}$$

$$i\hbar\frac{\partial \rho}{\partial t} = -\frac{\hbar^2}{2M}\left[\Psi^*\nabla^2\Psi - \Psi\nabla^2\Psi^*\right] + i\left[2W\rho\right] = -i\hbar div\vec{j} + i\left[2W\rho\right]$$

Quantum Mechanical Current Density

$$\vec{j} = \frac{\hbar}{2im}(\Psi * \vec{\nabla}\Psi + \Psi\vec{\nabla} * \Psi*)$$

$$= \frac{\hbar}{2im}(\Psi * \vec{\nabla}\Psi - \Psi\vec{\nabla}\Psi*)$$

$$div\vec{j} = \frac{\hbar}{2im}(\vec{\nabla}(\Psi * \vec{\nabla}\Psi) - \vec{\nabla}(\Psi\vec{\nabla}\Psi*))$$

$$= \frac{\hbar}{2im}(\Psi * \nabla^2\Psi + (\vec{\nabla}\Psi*)(\vec{\nabla}\Psi) - \Psi\nabla^2\Psi * -(\vec{\nabla}\Psi)(\vec{\nabla}\Psi*))$$

$$= \frac{\hbar}{2im}(\Psi * \nabla^2\Psi - \Psi\nabla^2\Psi*)$$

Mean Free Path in Strong Field (2)

- We get balance equation of QM flow:

$$\partial \rho / \partial t = -\mathrm{div}(\mathbf{j}) + (4\pi/h)W(r)\rho(r,t) \qquad (3)$$

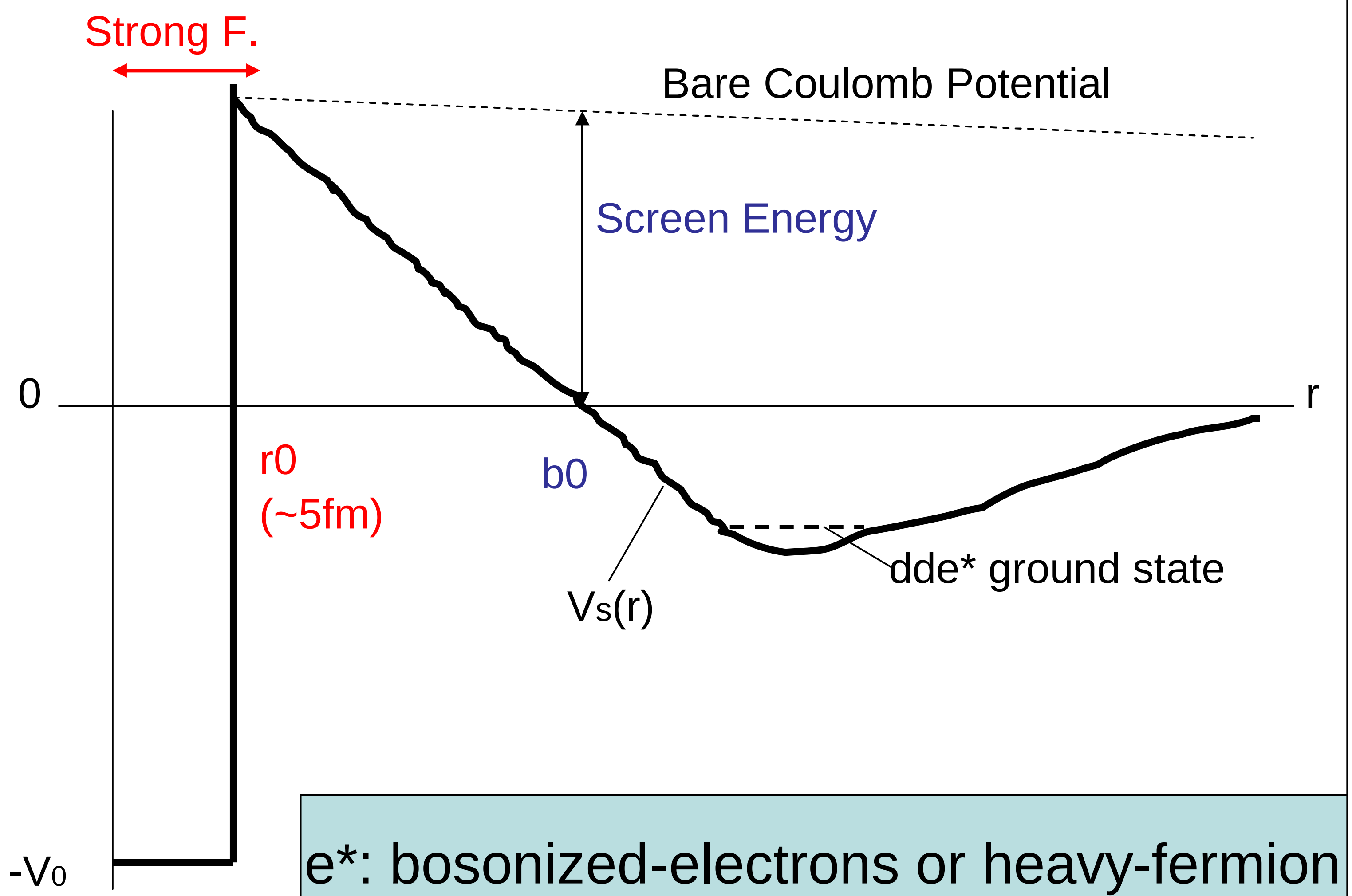
Here $\rho(r,t) = \Psi\Psi^*$: particle density and 2nd right hand side term shows absorption rate.

- Mean free path:

$$\Lambda = (h/4\pi)v/W(r) \qquad (4)$$

$$= \text{(velocity)x(life time)}$$

Steady State Molecule dde*



e*: bosonized-electrons or heavy-fermion

Steady dde* molecule - 1

- $\langle \text{Reaction Rate} \rangle_n = 1/\langle \text{mean life} \rangle$

  $= \langle \text{velocity} \rangle / \langle \text{mean free path in Strong Force Range} \rangle$

- $\langle \text{mean free path in strong force range} \rangle$

  $= \langle hv/2\pi \rangle / \langle f \mid 2W(R) \mid i \rangle$

  by balance of QM density flow.

- **$T_n = \langle \text{Reaction Rate} \rangle_n = (4\pi/h)\langle f \mid W(R) \mid i \rangle$**

Fusion Rate for Steady dde* molecule -2

- **<Fusion Rate per pair> = $T_n |\Psi(r0)|^2$**

$T_n = (4\pi/h)\langle\Psi_f|W(R)|\Psi_i\rangle / \langle\Psi_f|\Psi_i\rangle$

W(R) : imaginary part of nuclear optical potential

$H_{int} = U(R) = V(R) + iW(R)$

$|\Psi(r0)|^2$: (Coulomb barrier penetration probability at R=r0)

R: d-d distance

Comment by A.T.

Fusion Rate for Collision Process
- dynamic or transient process -

- **$T = \langle \Psi_f \mid H_{int} \mid \Psi_i \rangle$**

  = <Initial State Interaction>

  x<Intermediate Compound State>

  x<Final State Interaction>
- **Cross Section ~ T^2** ρ (E')
- ρ (E'): final state density
- **Reaction-Rate(σv): ($4\pi^2$/h)vT^2 ρ (E')**
- <Initial> = <El. EM Int><Strong Int>
- <Final>=BRs to Irreversible Decays

Text Books for Golden Rules

- E. Fermi: **Nuclear Physics**, Chapter V, The University of Chicago Press, 1950

- Easy Summary is given in:

C. J. Pethick, H. Smith: **Bose-Einstein condensation in dilute gases**, Chapter V, Cambridge University Press, 2002

Part II: Example-EQPET/TSC

- Adiabatic Treatment (Born-Oppenheimer)
- Barrier Penetration - Gamow Integral
- Tetrahedral Symmetric Condensate
- EQPET molecules and Potentials
- Strong Interaction for Multi-body Fusion
- Final State Interaction
- Time Dependent Squeezing of TSC
- Average Fusion rates
- Metal Nucleus + TSC Reactions

Fusion Rate of D-Cluster

Takahashi: Recent Res. Devel. Physics, 6(2005)1

① : **D-Cluster Formation Process:**

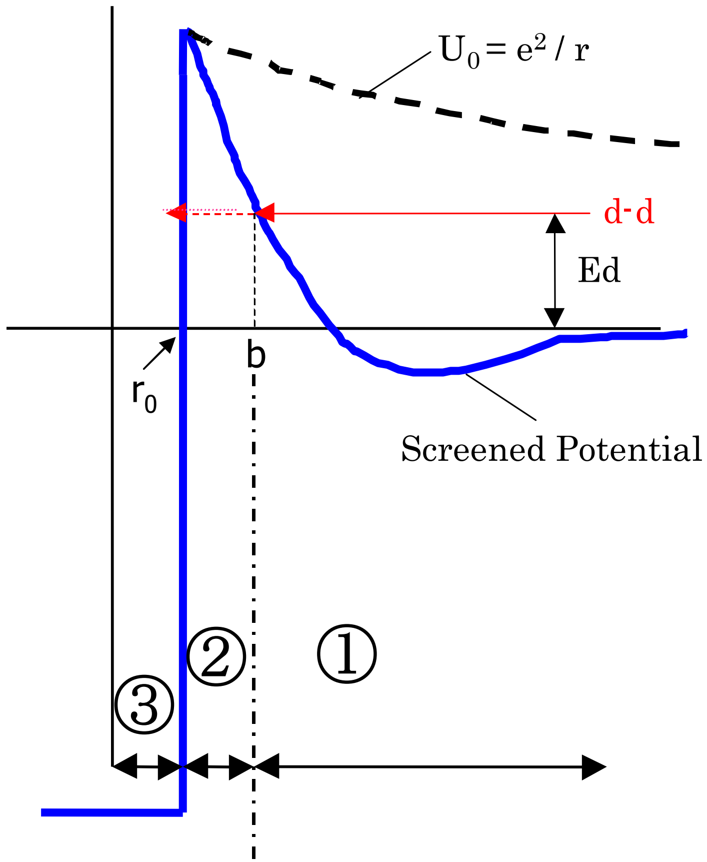
$F_{nD} = \langle \Psi 1^2 \rangle \langle \Psi 2^2 \rangle \langle \Psi 3^2 \rangle *** \langle \Psi n^2 \rangle$

② : **Barrier Penetration Process:**

$P_B = \exp(-n\Gamma_n)$

③ : **Nuclear Fusion Process**

$\sigma = S_{nD} / E_d$



$< \text{Fusion Rate} > = \sigma v * P_B * F_{nD}$

D+(D+(D+D))⇒ 4D

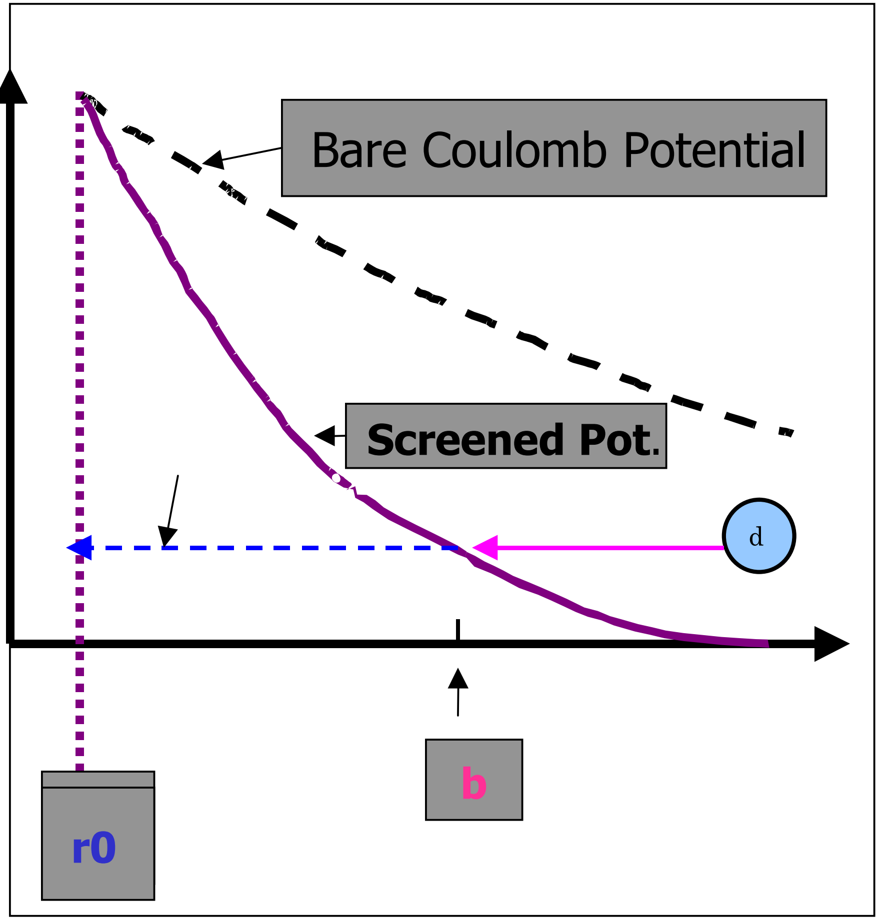
For T-Matrix Elements:
(1) And (2): EM Interaction, (3): Strong Interaction

Barrier Factor for Screened Potential

Gamow Integral over b to r0

$\Gamma_n = (2\mu)^{1/2}/h \int (V_s(r) - E_d)^{1/2} dr$

- $V_s(r)$: Screened Potential for a d-d pair in a TRF or ORF cluster of n deuterons
- b is important parameter to be estimated
- b should be far less than 70 pm
- r0 is about 5 fm for contact surface reaction of strong interaction



Text book: See E. Fermi's Nuclear Physics

Gamow Integral – (1)

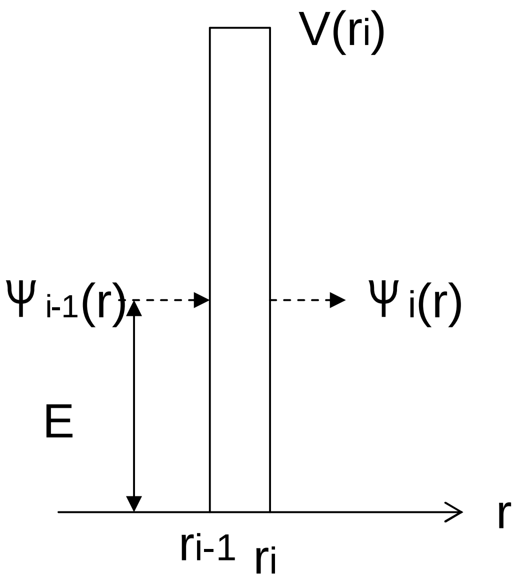


Fig: Very thin potential

- $-(h^2/8\pi\mu)\nabla^2\Psi + V(r)\Psi = E\Psi$ (1)

- $(1/\mu) = (1/m1) + (1/m2)$
- $V(r) = V(r_i)$; $r_{i-1} < r < r_i$

  $= 0$; $r < r_{i-1}$ or $r > r_i$
- $\Delta r_i = r_i - r_{i-1}$

- Set $\Psi(r) = \Phi(r)/r$
- $\Phi(r) = \exp(ikr)$; $r < r_{i-1}$
- $\Phi(r) = X(r)\exp(ikr)$; $r_{i-1} < r < r_i$ (2)
- $k = (2\mu E)^{1/2}/(h/2\pi)$

- $-(h^2/8\pi\mu)(\partial^2\Phi/\partial r^2) + (V(r) - E)\Phi = 0$ (3)

Gamow Integral – (2)

- Substituting (2) to (3) and eliminating exp(ikr),
- $-(h^2/8\pi\mu)(\partial^2 X/\partial r^2) + (V(r_i) - E)X = 0$ (4)

- $X(r) = \exp(-[(8\pi\mu)^{1/2}/h][V(r_i) - E]^{1/2}\Delta r_i)$ (5)

- Transmission Probability T_i

- $T_i = |\Phi(r_i)|^2 / |\Phi(r_{i-1})|^2$

  $= \exp(-[(8\pi\mu)^{1/2}/h][V(r_i) - E]^{1/2}\Delta r_i)$ (6)

Gamow Integral –(3)

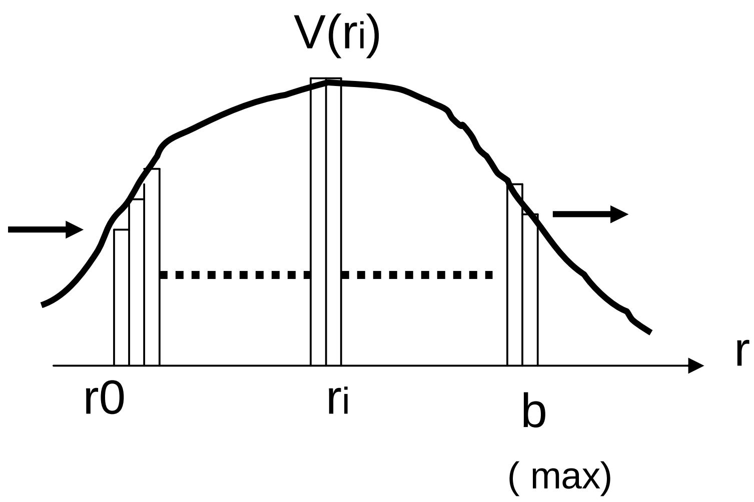


Fig: general potential function

- Penetration Probability P(E)

- $P(E) = T_1 T_2 T_3 T_4 \dots\dots\dots T_{max}$
  $= \exp(-[(8\pi\mu)^{1/2}/h] \sum_{i=1}^{max} [V(r_i) - E]^{1/2} \Delta r_i)$

By the definition of Lebesque integral:

$$P(E) = \exp(-[(8\pi\mu)^{1/2}/h] \int_{r0}^{b} [V(r) - E]^{1/2} dr)$$

For integral interval from r0 to b.

Basic Mechanism (Takahashi Model)

- **Tetrahedral Symmetric Condensate (TSC)**:

  4d+4e can squeeze to Transient Bose Condensation (TBC),

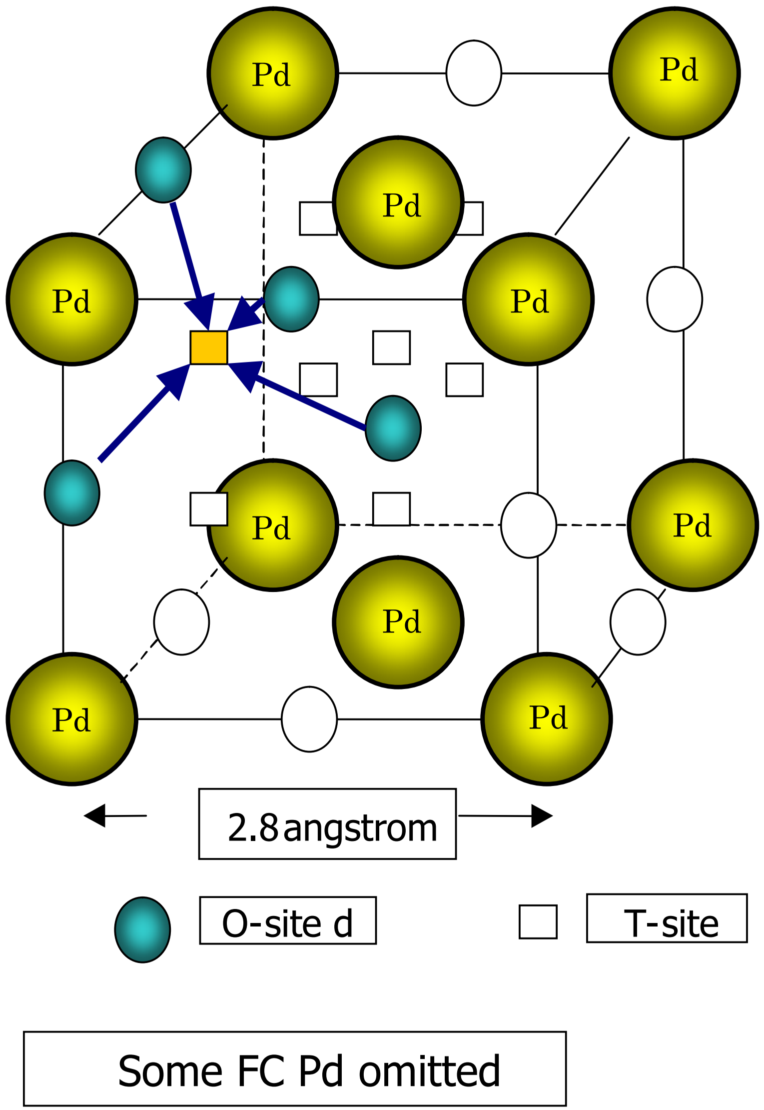
  under 3-Demensional Symmetric Constraint at some site in CM, to form a very small Charge-Neutral Pseudo-Particle

Tetrahedron and Octahedron

Regular Tetrahedral Arrangement

Regular Octahedral Arrangement

Tetrahedral Condensation of D-Cluster



Transient Bose Condensation of Deuterons

From O-site to T-site

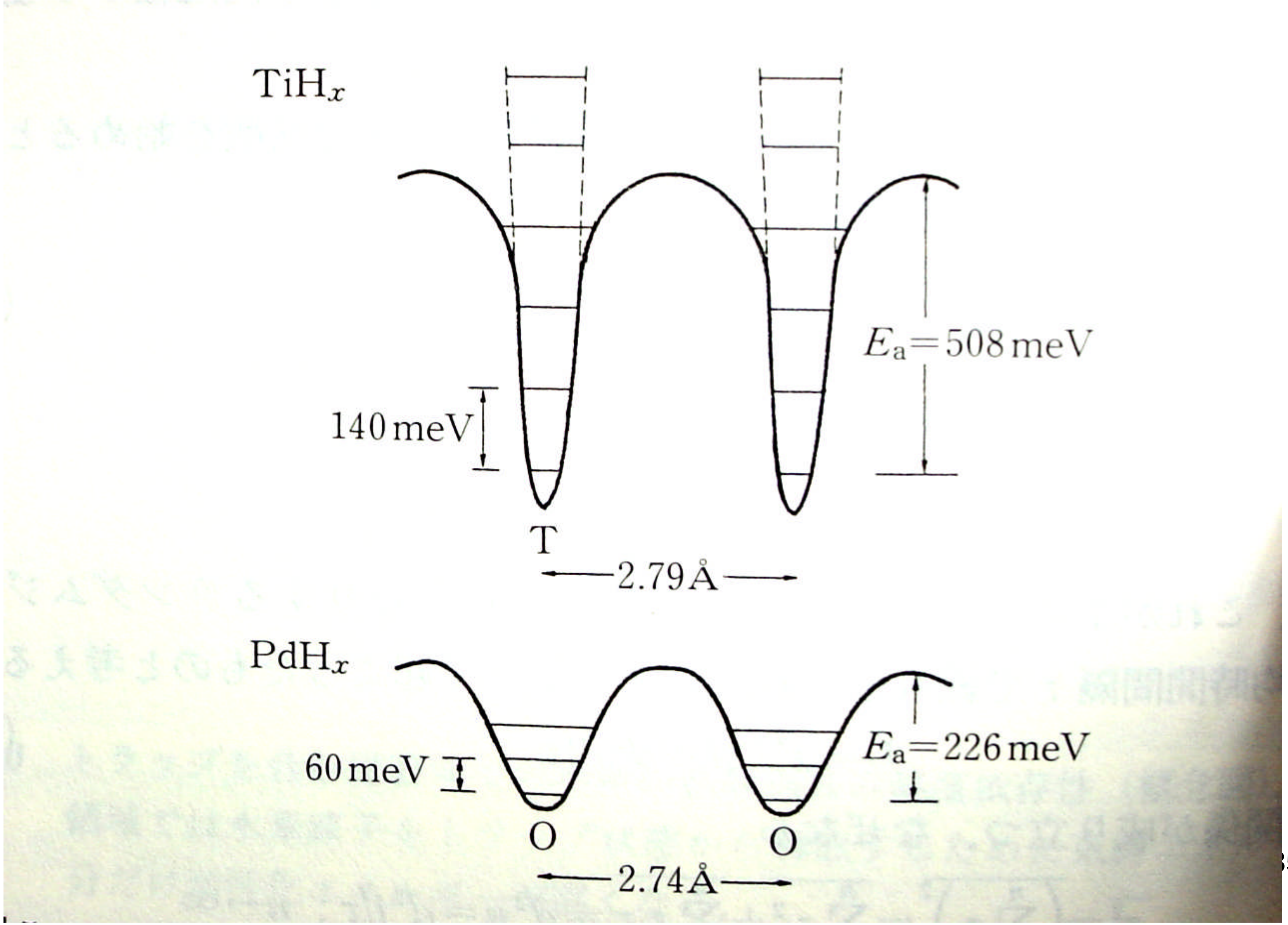
Associating Transient Squeezing (Bosonozation) of 4d-shell Electrons

Generation of Short-Life Quasi-Particle e* like Cooper-pair

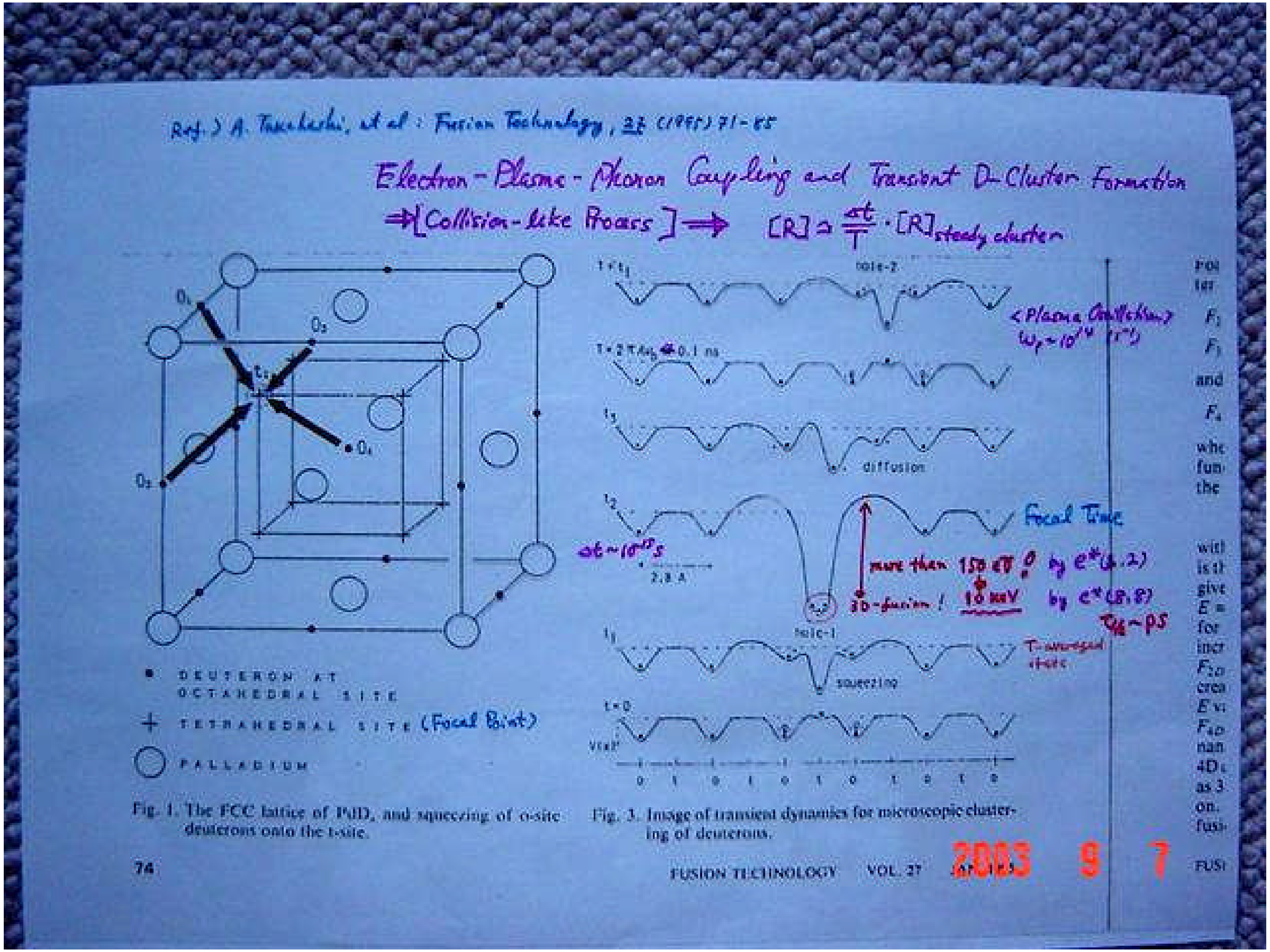
D-Cluster as Mixture of DDe, DDee, DDe*,DDe*e*

H-Trapping Potentials for Ti and Pd

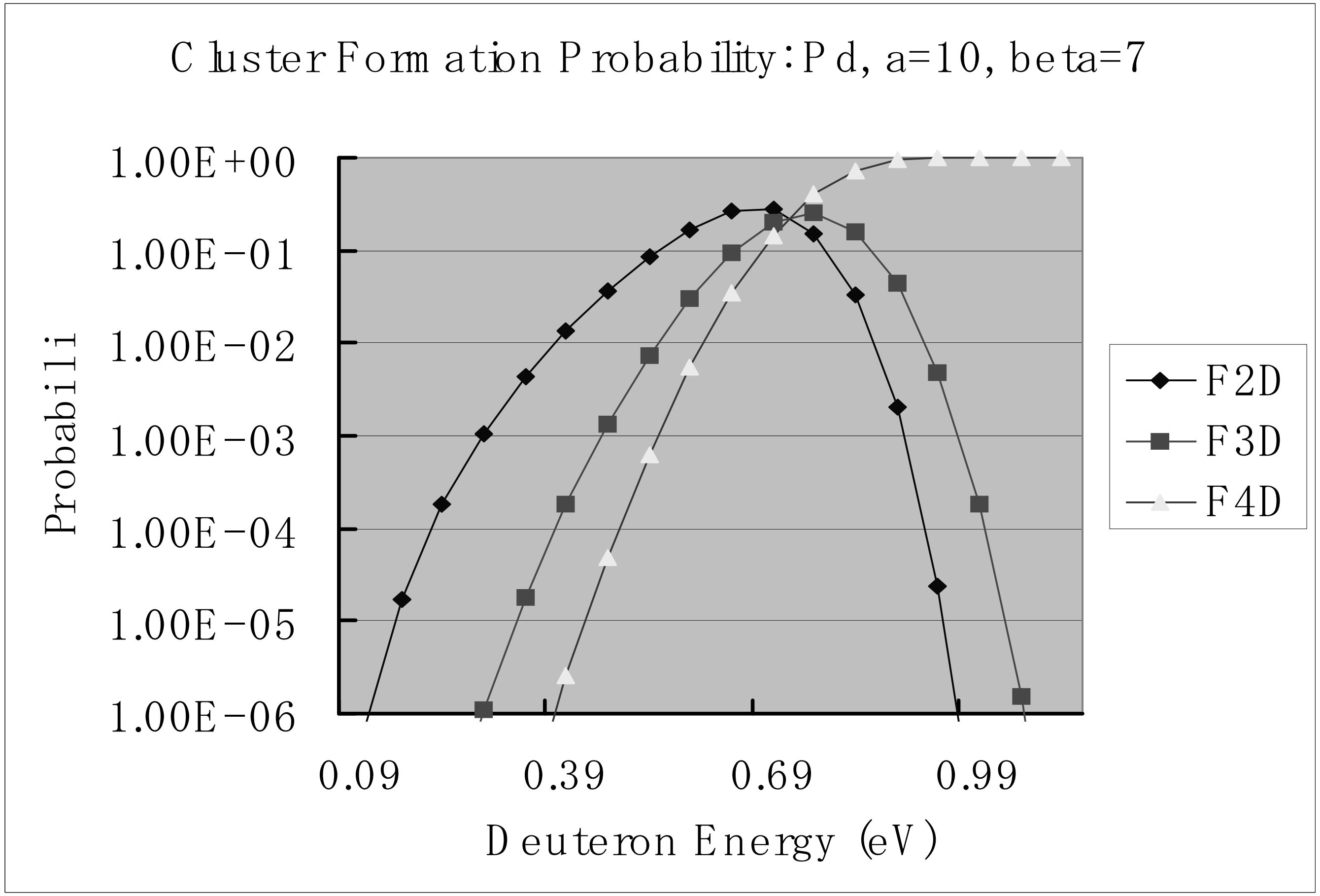
(Y. Fukai, 1998)



D-Cluster Formation in PdD Transient Dynamics by Phonon Excitation



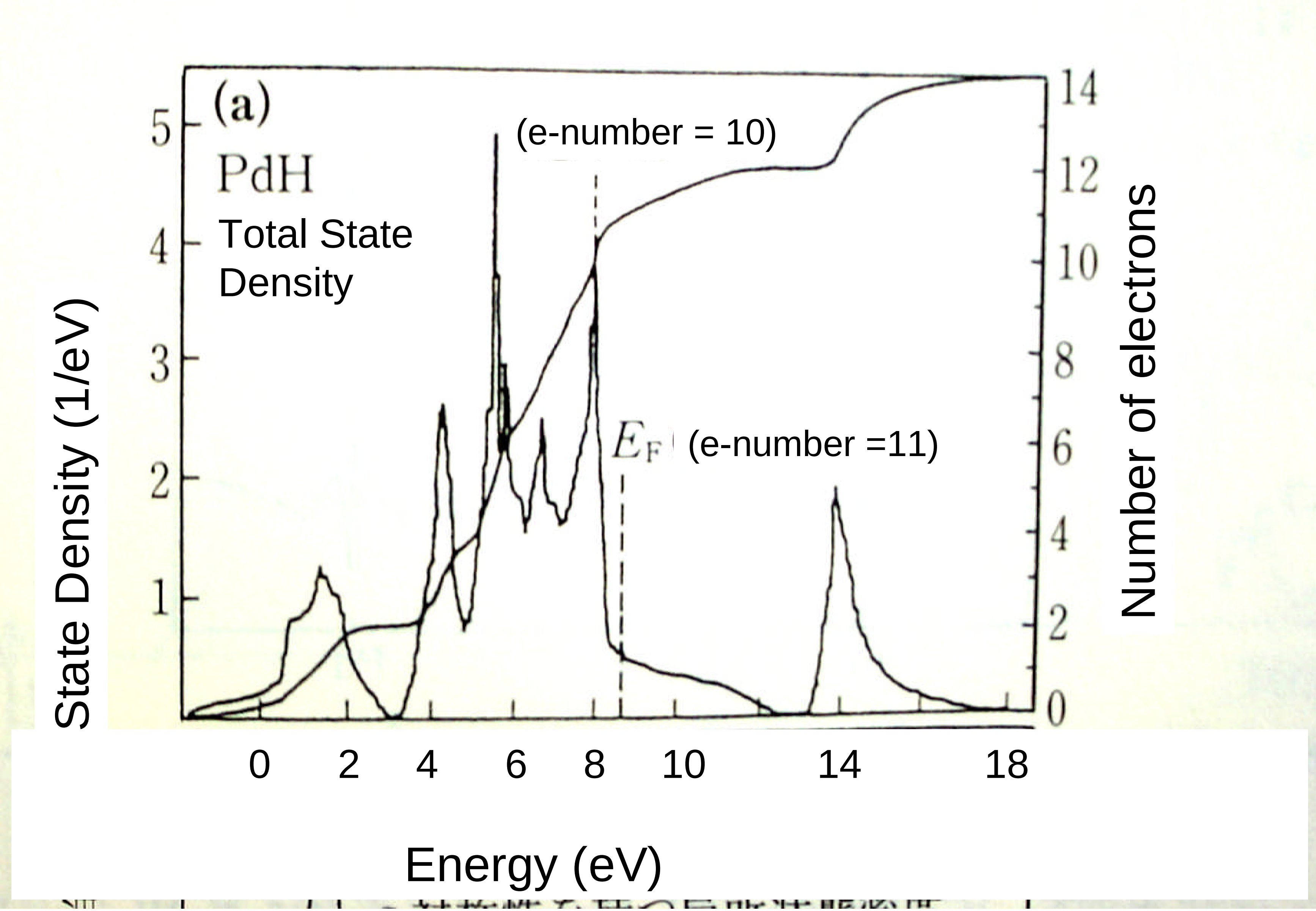
Cluster Formation Probability in Atomic Level



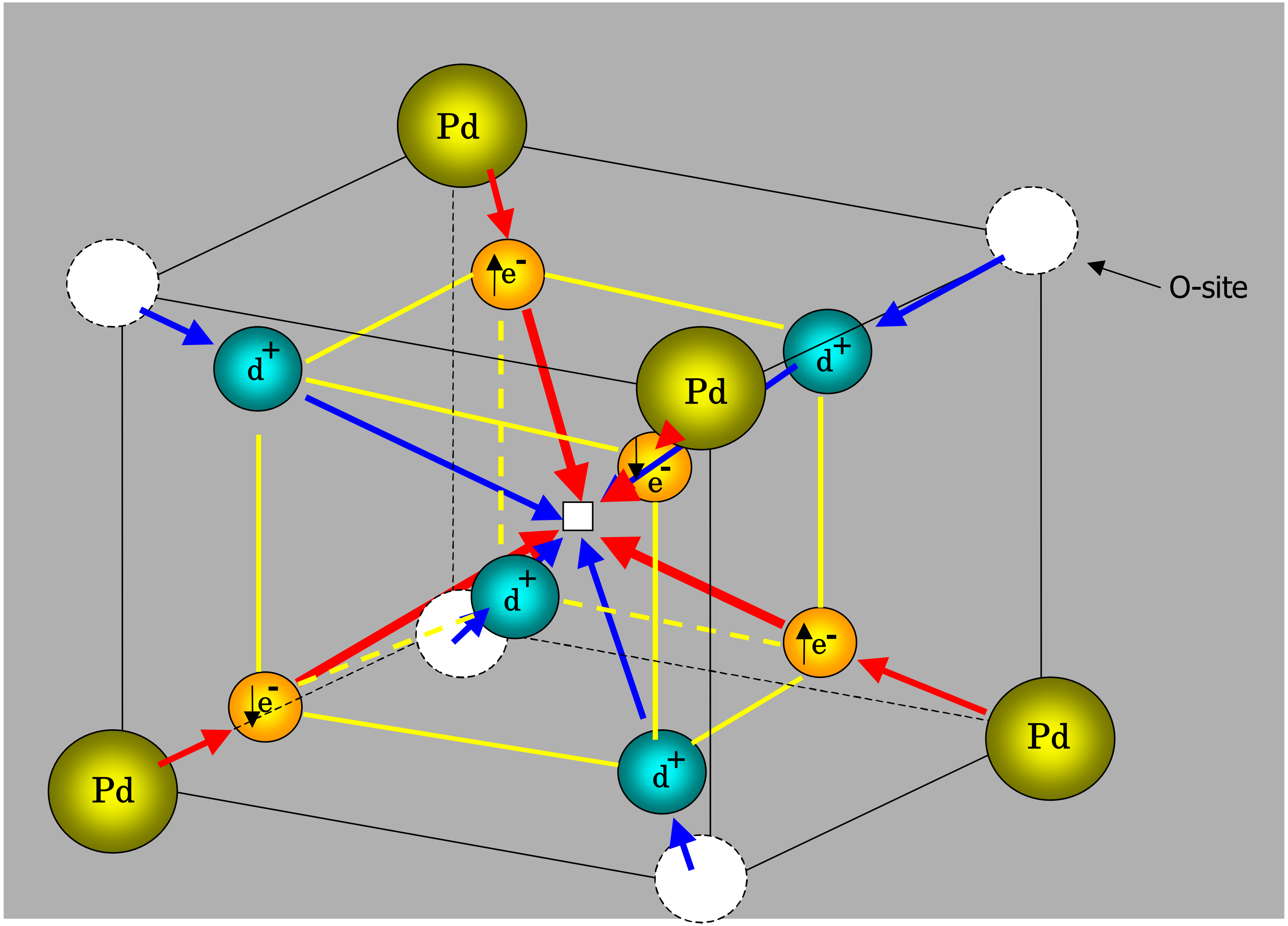
•Calculation by Excitation Screening Model

One Phonon Energy = 64 meV for D Harmonic Oscillator

Electron Sates in PdH (by Y. Fukai, 1998)
Proton (Deuteron) behaves as if Atom (p + e)

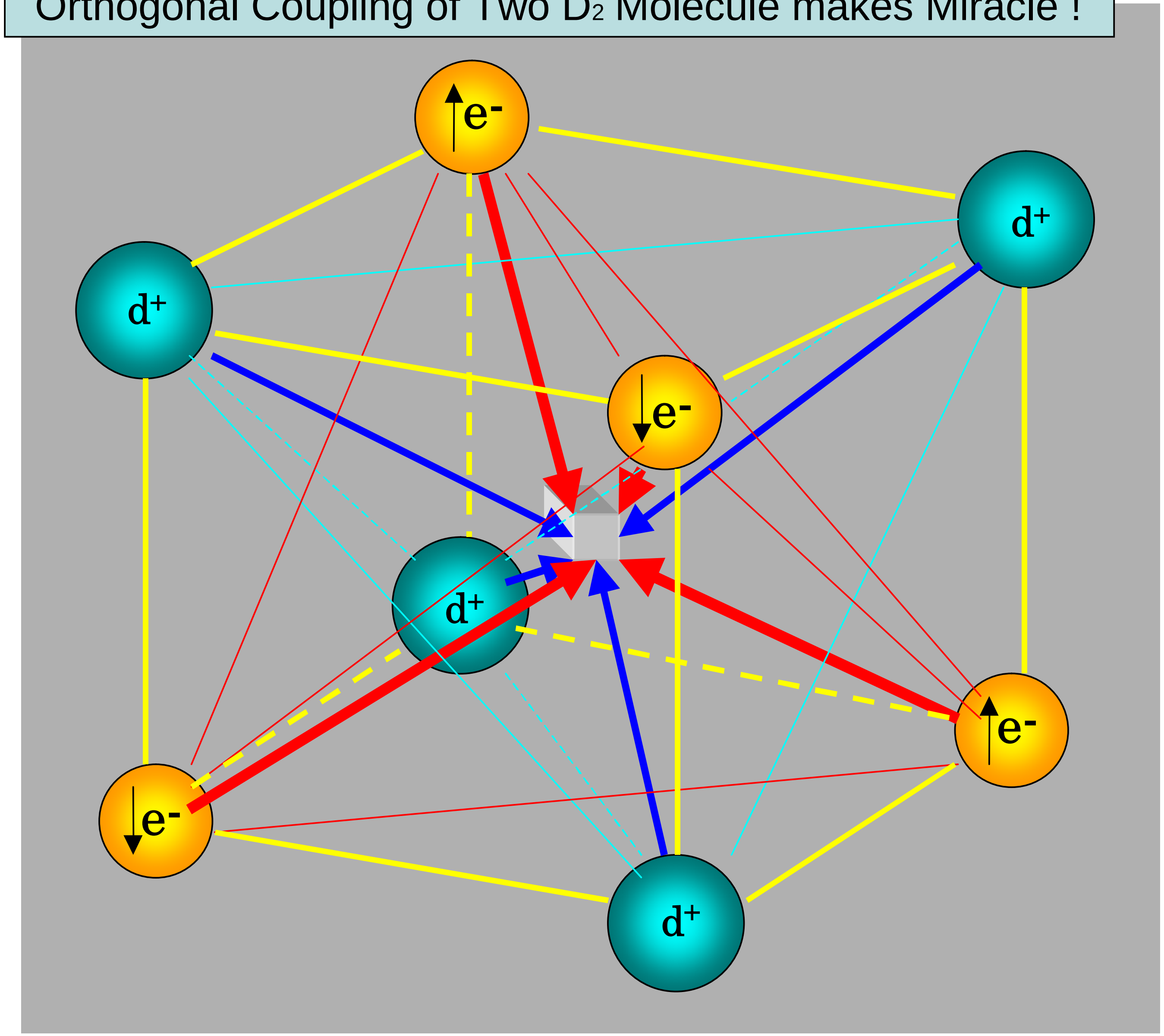


Tetrahedral Condensation of Deuterons in PdDx



Classical View of Tetrahedral Sym. Condensation

Orthogonal Coupling of Two D_2 Molecule makes Miracle !



Transient Combination of Two D2 Molecules (upper and lower)

Squeezing only from O-Sites to T-site

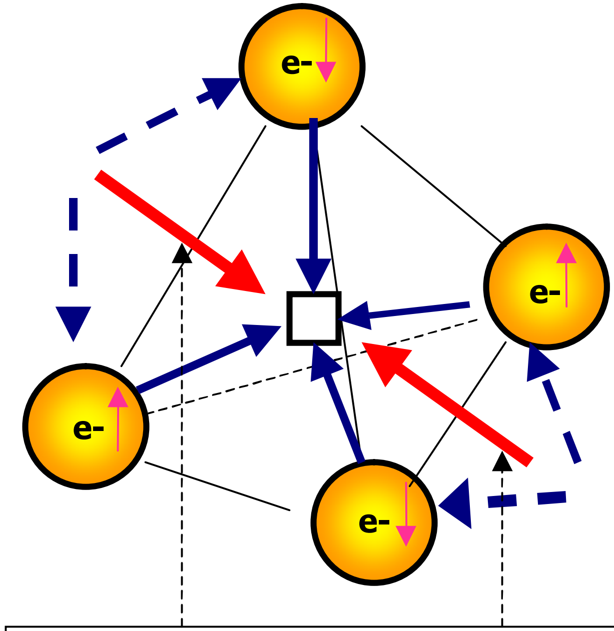
3-dimension Frozen State for 4d+s and 4e-s

Quadruplet e* (4,4)

Formation of Electrons around T-site

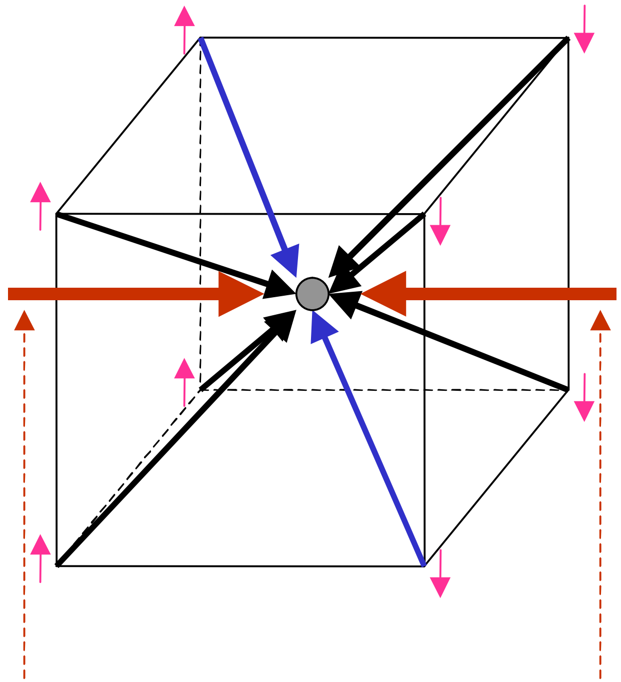
Quadruplet and Octal-Coupling of Electrons

Quadruplet e*(4,4)



Sum Momentum Vector

Octal-Coupling e*(8,8)



Sum Momentum Vector

EQPET: Electronic Quasi-Particle Expansion Theory

- Wave functions of TSC or OSC cluster can be approximated by linear combination of partial wave functions for normal and quasi-molecular states, dde, ddee, dde* and dde*e*.
- 4D and 8D clusters are composed of dde, ddee, dde*, dde*e*,…molecules.

EQPET: continued-1

"Bosonized" electron wave function Ψ_N for N-electrons system in MDx lattice will be approximated by a linear combination of normal electron wave function $\Psi_{(1,1)G}$ and quasi-particle wave functions $\Psi_{(2,2)G}$ $\Psi_{(4,4)G}$ and $\Psi_{(8,8)G}$ as;

$$|\Psi_N> = a_1 | \Psi_{(1,1)G}> + a_2 | \Psi_{(2,2)G}> + a_4 | \Psi_{(4,4)G}> + a_8 | \Psi_{(8,8)G}> \qquad (3)$$

For the time-window of potential deep hole [1,2], effective (time-averaged) screening potential, for a d-d pair in a transient D-cluster of 4-8 deuterons for TRF and ORF condition [2], can be defined by a screened potential of quasi-particle complex;

$$V_s(R) = b_1 V_{s(1,1)}(R) + b_2 V_{s(2,2)}(R) + b_4 V_{s(4,4)}(R) + b_8 V_{s(8,8)}(R) \qquad (9)$$

EQPET: continued-2

For a dde* or dde*e* molecule,

wave function of a d-d pair (2D) is given by the solution of the following Schroedinger equation:

$$(-h^2/(8\pi\mu))\nabla^2 \chi(R) + (V_n(R) + V_s(R))\chi(R) = E\chi(R) \qquad (11)$$

By Born-Oppenheimer approximation, we assume as,

$$\chi(R) = \chi_n(R)\chi_s(R) \qquad (12)$$

Overlapping rate of $\chi(R)$ at R = r0 gives estimation of d-d fusion rate λ_{2d} as:

$$\lambda_{2d} = G\,|\chi(R)|^2_{R=r0}$$
$$= G\,|\chi_n(R)|^2_{R=r0}\,|\chi_s(R)|^2_{R=r0} \qquad (13)$$

EQPET: continues-3

Using WKB approximation for the barrier ($V_s(R)$) penetration probability,

$$|X_s(R)|^2_{R=r0} = \exp(-2\Gamma_n(E_d)) \quad (14)$$

;Barrier Factor (BF)

where E_d is the relative deuteron energy and Γ_n is Gamow integral for a d-d pair in D-cluster (n-deuterons with electrons) that is defined as:

$$\Gamma_n(E_d) = (2\mu)^{1/2}/(h/\pi) \int_{r0}^{b}(V_s(R)-E_d)^{1/2}dR \quad (15)$$

Using astrophysical S-factor for strong interaction,

$$G|X_n(R)|^2_{R=r0} = vS_{2d}(E_d)/E_d \quad (16)$$

Consequently we can approximately define fusion rate as:

$$\lambda_{2d} = (vS_{2d}(E_d)/E_d) \exp(-2\Gamma_n(E_d)) \quad (17)$$

Screened Potential of EQPET Molecule

Using the Single Particle Approximation, for e*, screened potential is given by applying solutions in Pauling's book:

For dde*,

$$V_s(R) = V_h + e^2/R + (J + K)/(1 + \Delta)$$

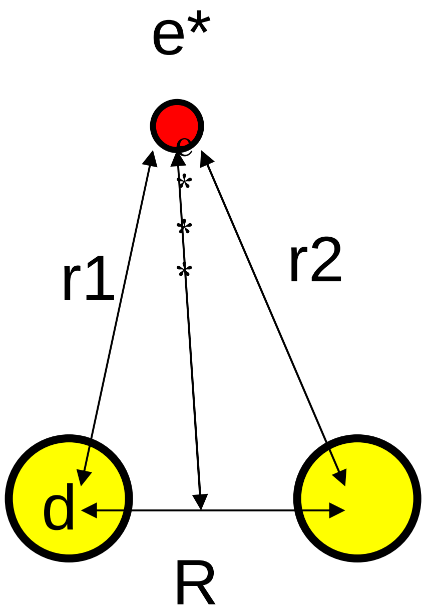
For dde*e*,

$$V_s(R) = 2V_h + e^2/R + (2J + J' + 2\Delta K + K')/(1 + \Delta^2)$$

For de*, $V_h = -13.6(e^*/e)^2(m^*/m_e)$

Screening Potential for dde* (1)

- EQPET Molecule dde*



- **e* : Quasi-particle of Bosonized electrons**
- **(m, Z) : Cooper pair : m= 2me, Z=2**
- **Quadru-pairing: m=4me, Z=4**e***
- **e*(m,Z)**
- **V_c(r, R)= 1.44/R – 1.44Z/r1 –1.44Z/r2**
- **: Coulomb Potential**
- **V_n(R) : Nuclear Potential**
- **$[-(h^2/8\pi M)\Delta_R - (h^2/8\pi m)\Delta_r - Ze^2/r1 - Ze^2/r2 + e^2/R + V_n(R) - E]\Psi = 0$**
- **For e-, neglecting ΔR and V_n,**
- **$[-(h^2/8\pi m)\Delta_r - Ze^2/r1 - Ze^2/r2 + e^2/R - \varepsilon(R)]\Phi(r,R) = 0$**
- **$\Psi(r,R) = \Phi(r,R) x X(R)$; Born-Oppenheimer Approx.**
- **.**
- **$[-(h^2/8\pi M)\Delta_R + \varepsilon(R) + V_n(R) - E]X(R) = 0$**
- **where, $V_s(R) = \varepsilon(R)$; screened Morse –like potential**

Screened Potential for dde* (2)

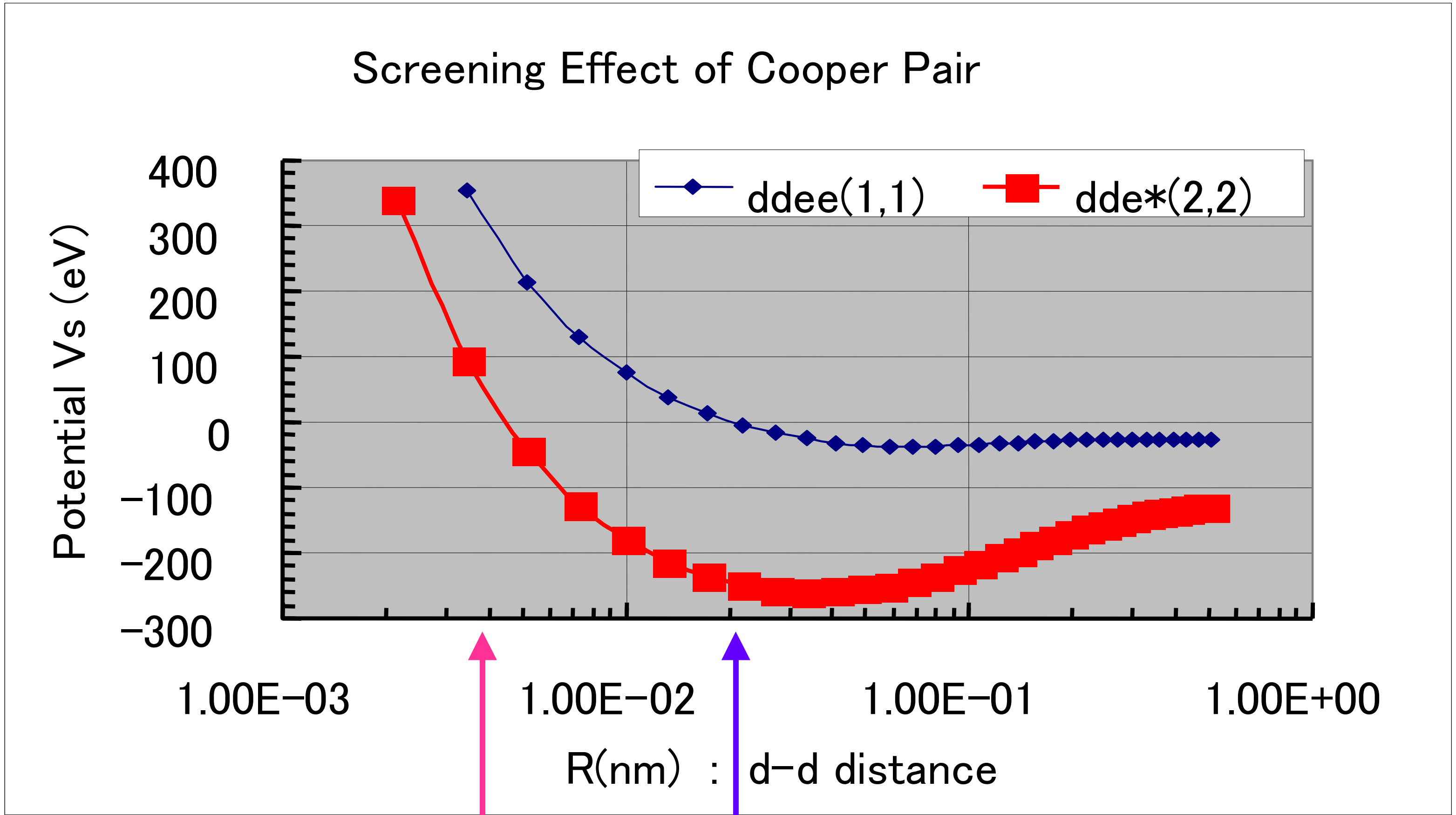
- **$\Phi(r,R)$ is set to linear combination of e* wave functions (1S-wave functions) for system1 and system2 deuteron as,**
- **$\Phi(r,R) = C_1 u_{1s1} + C_2 u_{1s2}$**
- **Using the variational principle, $\varepsilon(R) = V_s(R)$ is solved to be root of second-order secular equation (determinant of matrix = quadratic equation), as given in the QM text book of Pauling-Wilson, as;**
- **$V_s(R) = V_h + e^2/R + (J+K)/(1+\Delta)$**

- **Where, for fundamental modes of wave functions,**

$J = \langle u_{1s1} | (-Ze^2/r_2) | u_{1s1} \rangle = (Ze^2/a_0)[-1/y+(1+1/y)\exp(-2y)]$

- **$K = \langle u_{1s2} | (-Ze^2/r_2) | u_{1s1} \rangle = -(Ze^2/a_0)(1+y)\exp(-y)$**
- **$\Delta = \langle u_{1s1} | u_{1s2} \rangle = (1+y+y^2/3)\exp(-y)$**
- **With $y = R/(a_{0/Z/m^*/m_e})$ and**
- **$a_0 = 0.053$ nm.**
- **V_h is energy state of de* atom, i.e.,**
- **$V_h = -13.6(e^*/e)^2(m^*/m_e)$**
- **$(-\hbar^2/(2m)\nabla^2 u_{1s1} - (Ze/r)u_{1s1} - V_h u_{1s1} = 0$**

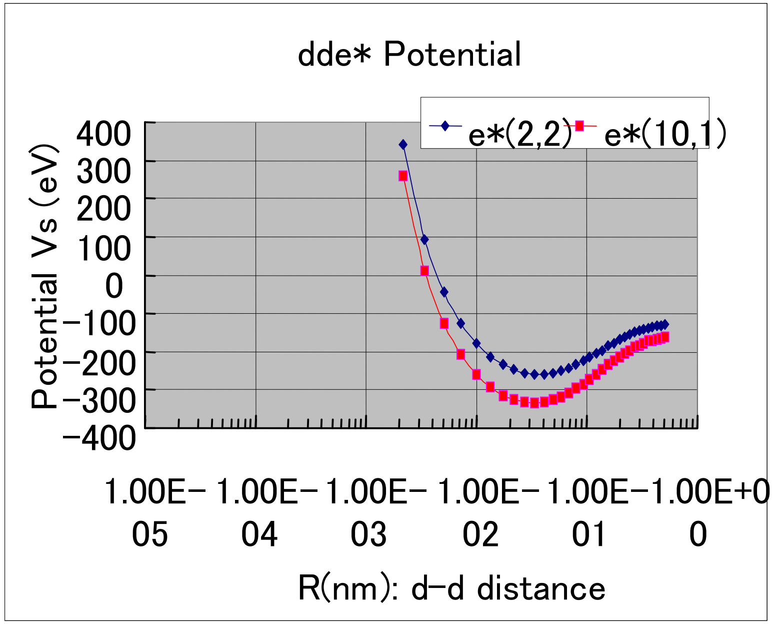
Screening Effect by EQPET Molecules

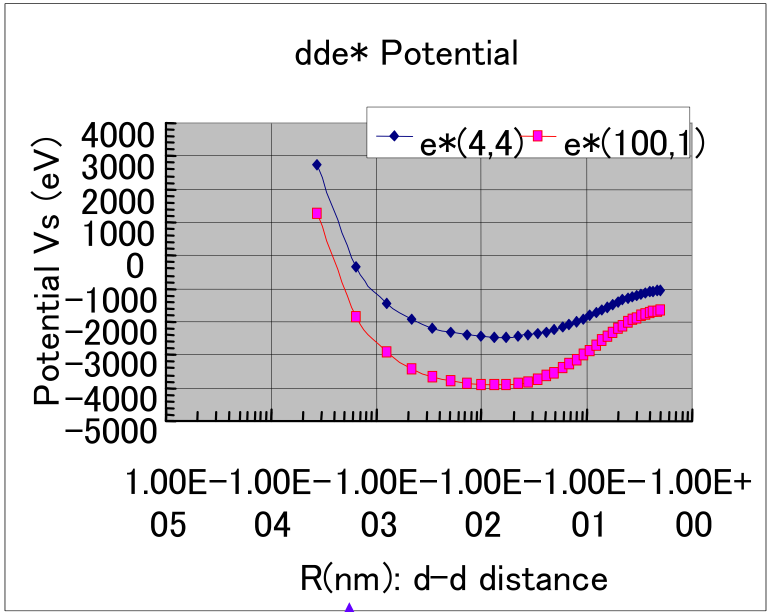


b(2,2) = 4 pm

b(1,1) = 20 pm

Screening Effect: EQPET Molecule vs. Heavy Fermion





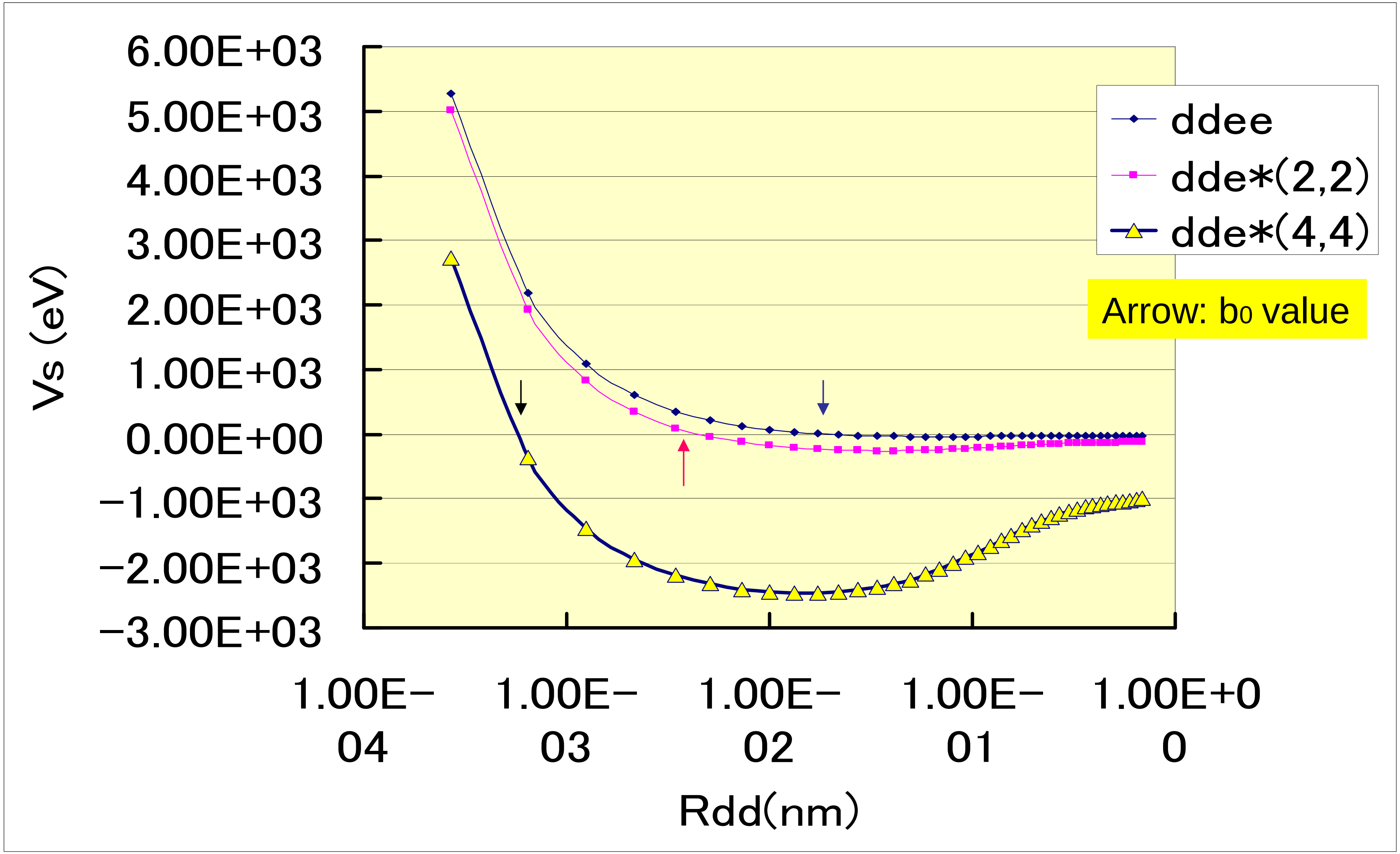
b(4,4) = 360 fm

Cooper pair (single particle) works as strong as mass 10 fermion

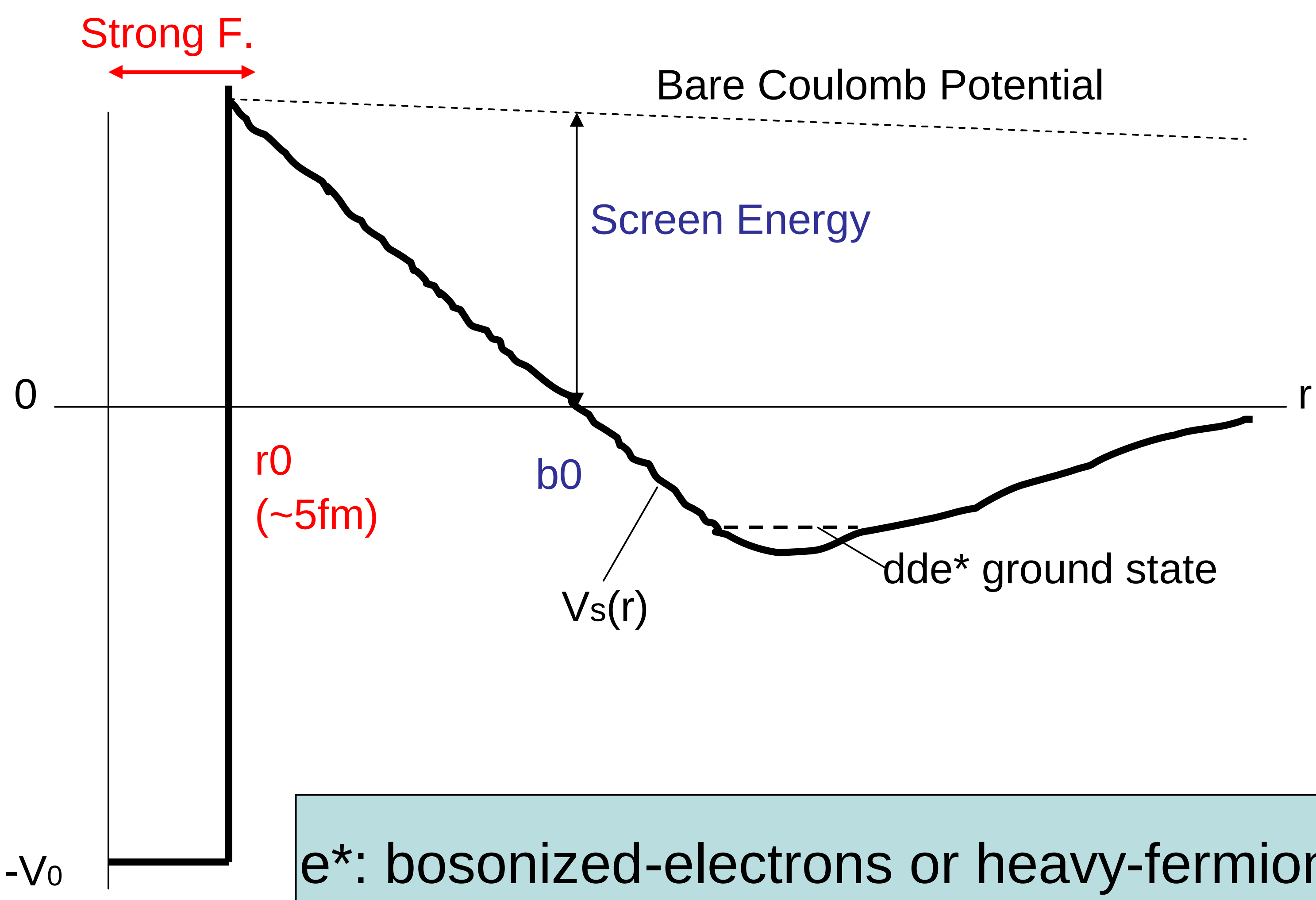
Pairing of e*(2,2)s works as strong as mass 100 fermion

e*(4,4)< μ (208,1)<e*(8,8)

Comparison of dde* potentials



Adiabatic Potential for Molecule dde*



e*: bosonized-electrons or heavy-fermion

Screening Energy of EQPET Molecules
$U_s = - e^2/b_0$ for $V_s(b_0) = 0$

	U_s (eV)	U_s(eV)	b_0 (pm)	b_0 (pm)
e*	dde*	dde*e*	dde*	dde*e*
(1,1)	36	72	40	20
(2,2)	360	411	4	3.5
(4,4)	4,000	1,108	0.36	1.3
(8,8)	22,154	960	0.065	1.5
(208,1)	7,579	7,200	0.19	0.20
(6, 6)	9,600		0.15	

Parameters of dde* potentials

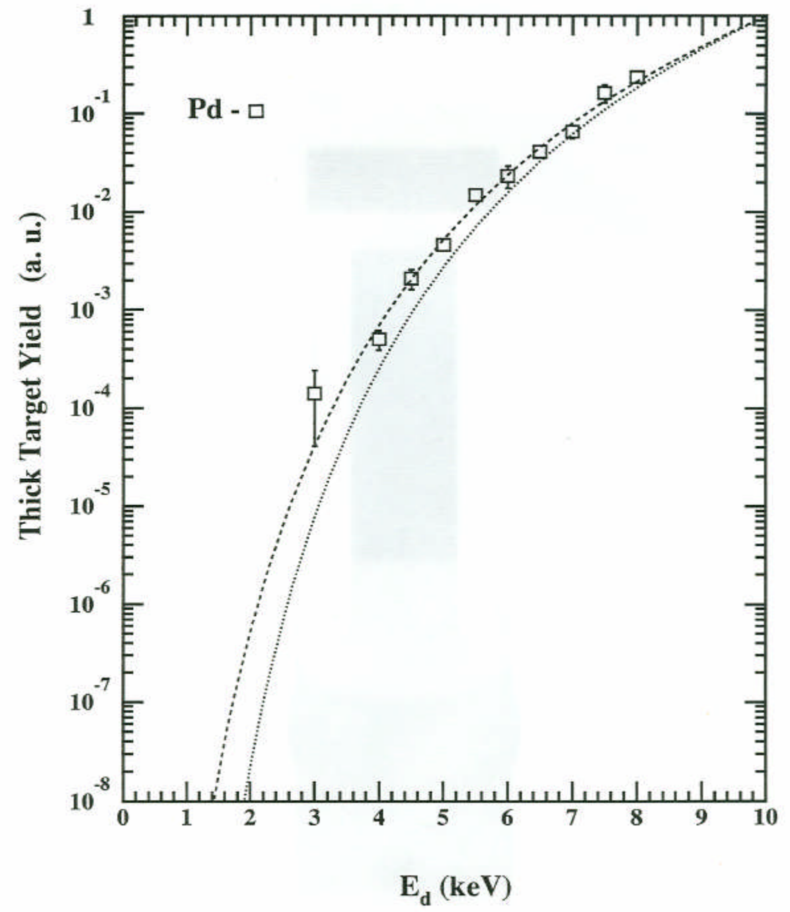
e*(m, Z)	V_{SMIN} (eV)	b_0 (pm)	R_{dd}(gs) (pm)
(1, 1)	- 15.4	40	101
(1, 1)x2; D_2	- 37.8	20	73
(2, 2)	- 259.0	4	33.8
(4, 4)	- 2,460	0.36	15.1

Trapping Depth

Ground State

Protein yield (α cross section) from deuterated Pd target

$D(d,p)^3H$ reaction with

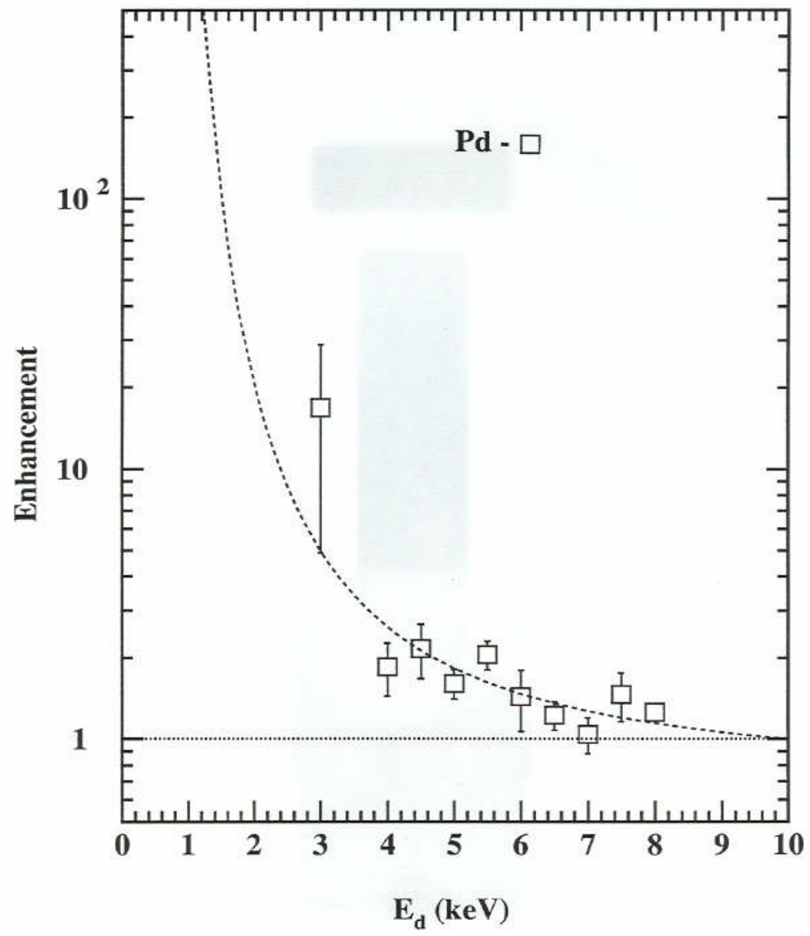


Deuteron Beam

Enhancement Factor:

exp $(-\sqrt{E_G/(E+U_e)})/\exp(-\sqrt{E_G/E})$

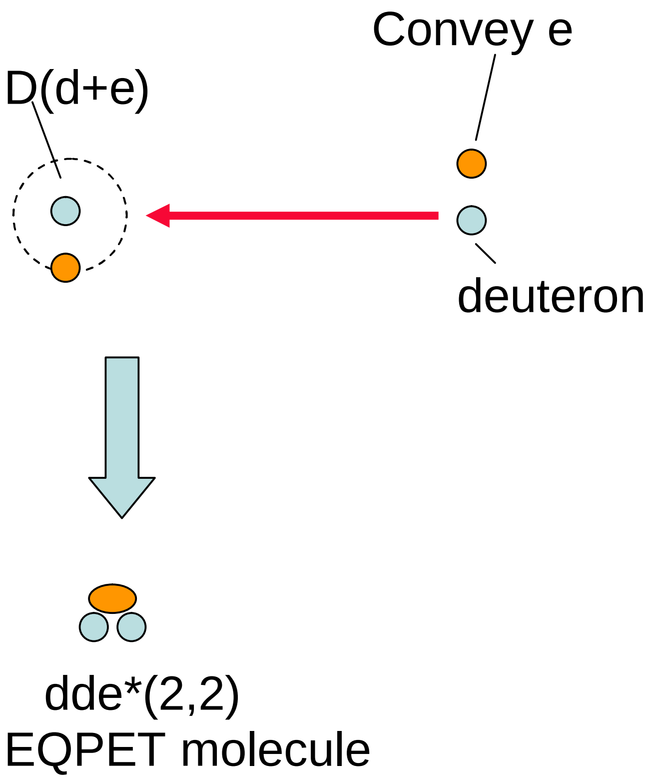
Us = 310 eV



Deuteron Beam

Kasagi et al: JPSJ, 71(2002)2881

Beam-Solid-Target reaction



- Formation of EQPET molecule dde*(2,2) with 50% anti-parallel spin arrangement for two electrons:

  U_s (Screening E) = 360eV

- Exp. with 1-10 keV D+ beam to PdDx, by Kasagi (2002):

  JSPS 71(2002)2881

  U_s = 310 +- 30 eV

Scaling of PEF (Pion Exchange Force) for Nuclear Fusion by Strong Interaction

Two Body Interaction: PEF = 1

$n + \pi^{+} \rightarrow p$

(udd) (ud*) (uud)

$p + \pi^{-} \rightarrow n$

(uud) (u*d) (udd)

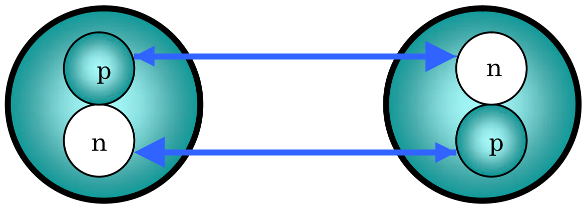
: u ; up quark

: d ; down quark

: u* ; anti-up quark

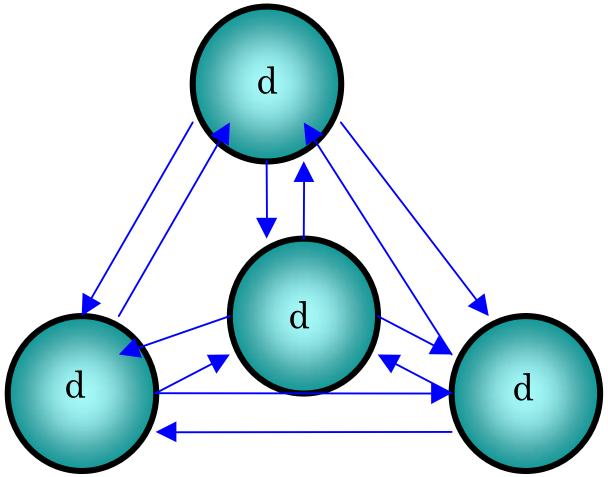
: d* ; anti-down quark

For D + D Fusion; PEF = 2

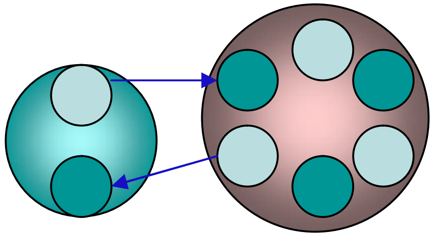


4D →^{8}Be* vs. D+^{6}Li → ^{8}Be* ; for strong interaction

4D Fusion; PEF = 12



D + ^{6}Li Fusion: PEF = 2+ α



4D Fusion has much larger Contact Surface of PEF than D+^{6}Li
with short range (few fm) charged-pion exchange

Estimation of S-value

- Scaling by PEF-values:

  $U(r) = V(r) + iW(r)$

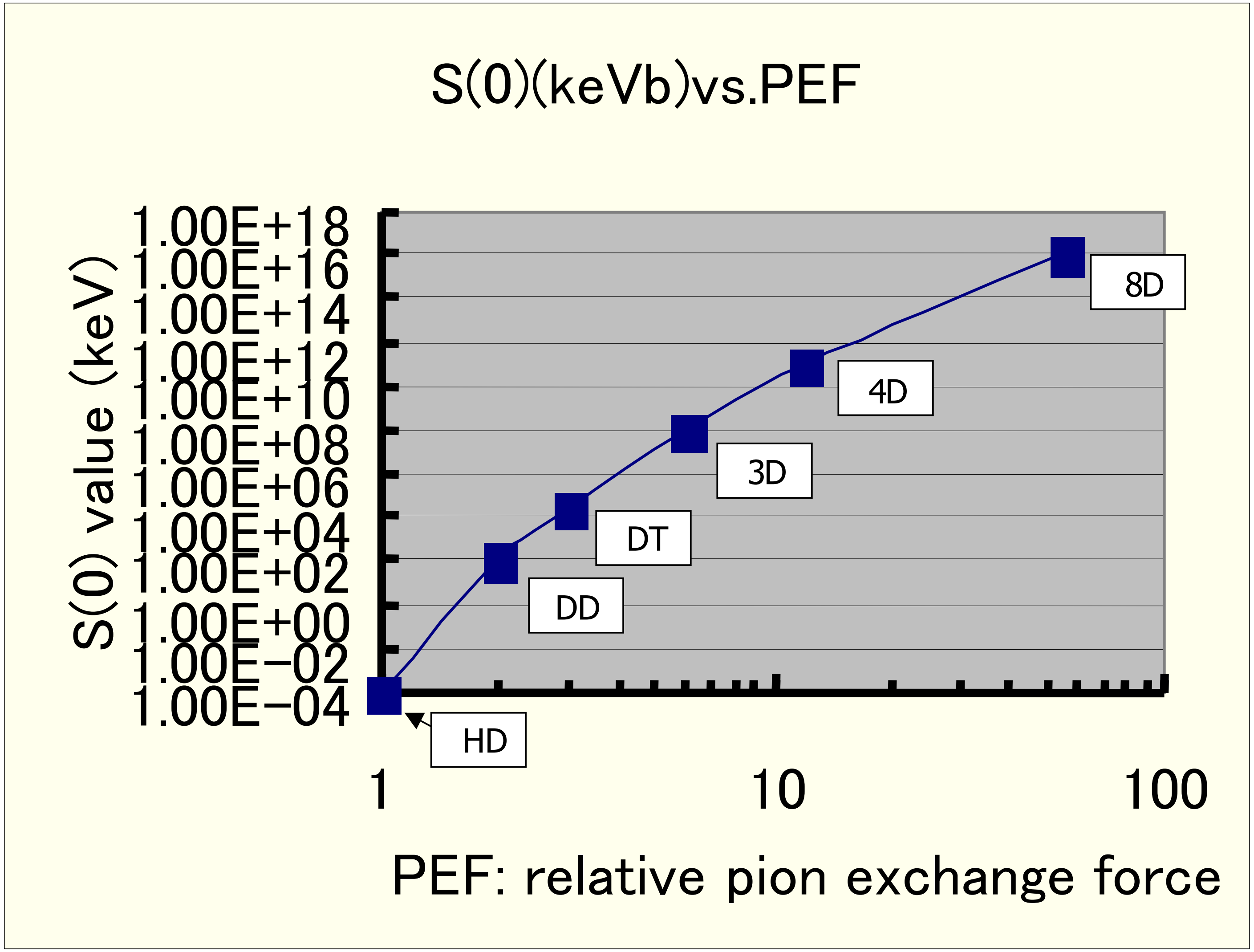
  $W(r) \sim W_0 \delta (r - r0)$

- PEF reflects size of contact sticking surface for fusion reaction by charged pion exchange:

  $S_n(0) \sim T_n^2 \sim (PEF)^N$

- S_{dd}=1.1E2 keVb, S_{dt} = 2E4 keVb, with PEF_{dd} =2, PEF_{dt}=3, PEF_{4d}=12
- N is roughly 11.4 to give S_{4d} = 1E11 keVb

Effective S(0)-values for Multi-Body D-Fusion



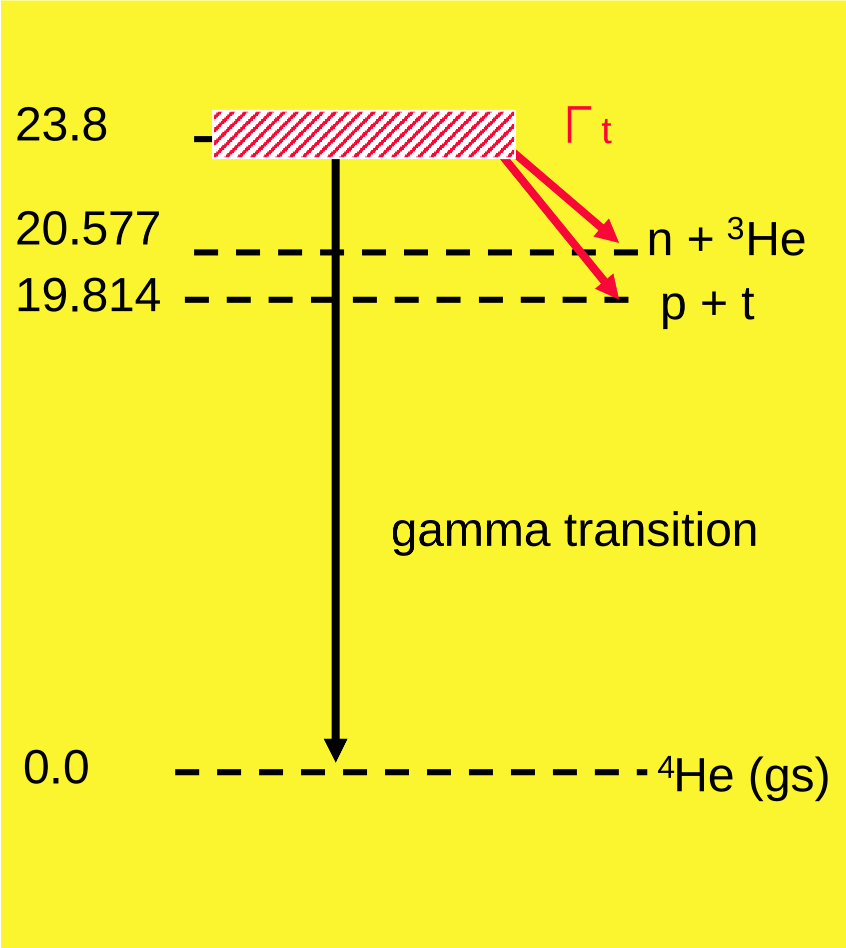
Barrier Factors (BF) and Fusion Rates (FR)

Ed = 0.22eV

(m*, e*)	Barrier Factor				Fusion Rate (f/s/cl)			
	2D	3D	4D	8D	2D	3D	4D	8D
(0,0)	E-1685				E-1697			
(1,1)	E-125	E-187	E-250	E-500	E-137	E-193	E-252	E-499
(2,1)	E-53	E-80	E-106	E-212	E-65	E-86	E-108	E-211
(2,2)	E-7	E-11	E-15	E-30	E-20	E-17	E-17	E-29
(4,4)	(3E-4)	E-5	E-7	E-14	(E-16)	E-11	E-9	E-13
(8,8)	(4E-1)	(2E-1)	(1E-1)	2E-2	(E-13)	(E-7)	(E-3)	E-1

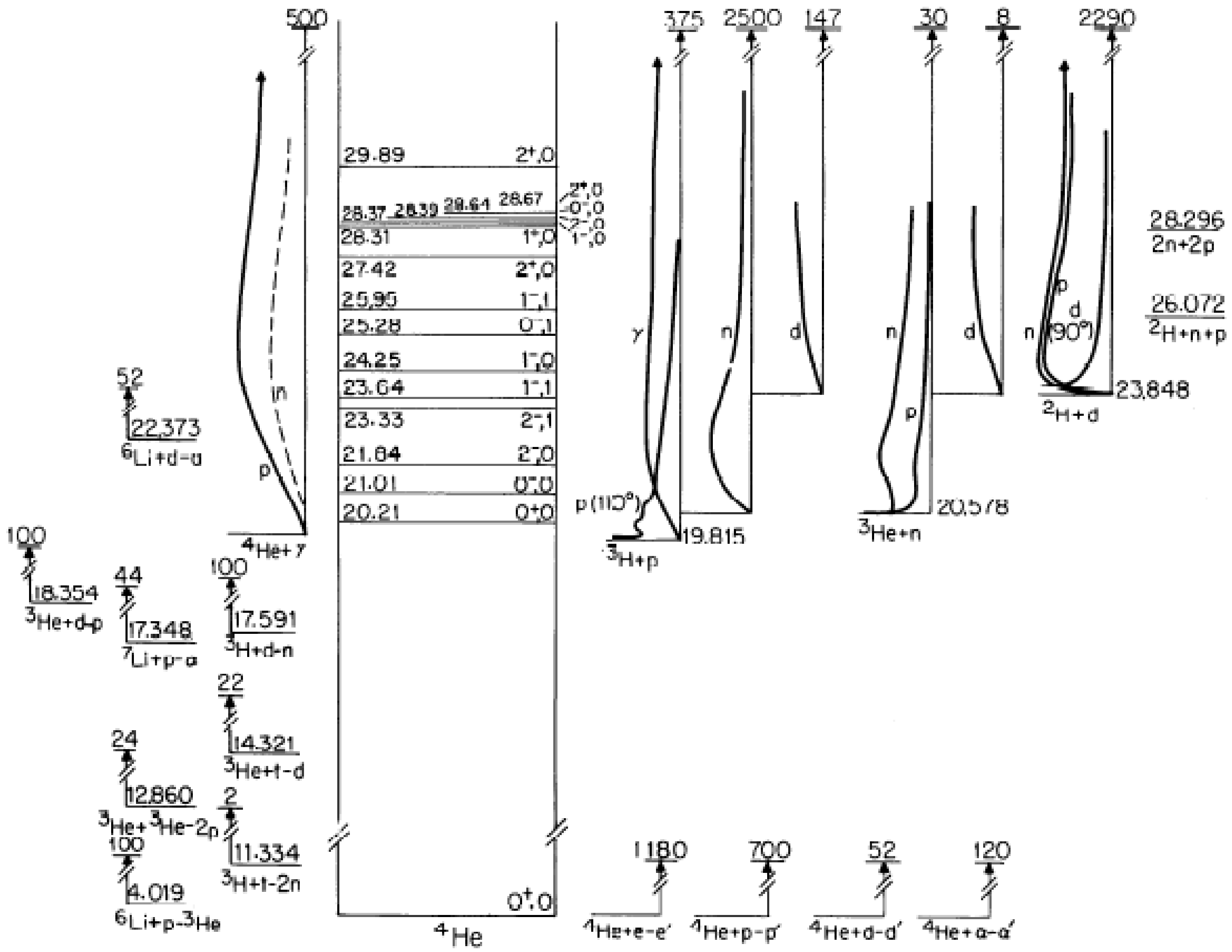
( ) is virtual rate

d + d → $^4He^*$(23.8MeV) → Break-up



- Branching Ratio : $S_n(0)/S_p(0)/S_g(0) = \Gamma_n/\Gamma_p/\Gamma_g$ = 0.5/0.5/0.0000001
- $\Gamma_n = \Gamma_p = 0.2$ MeV
- $\Gamma_g = 0.04$ eV
- $\Gamma_t = \Gamma_n + \Gamma_p + \Gamma_g$
- $\tau = h/\Gamma_t = 1E{-}22$ s
- No forces to change BRs have ever been proposed!

Level scheme of He-4



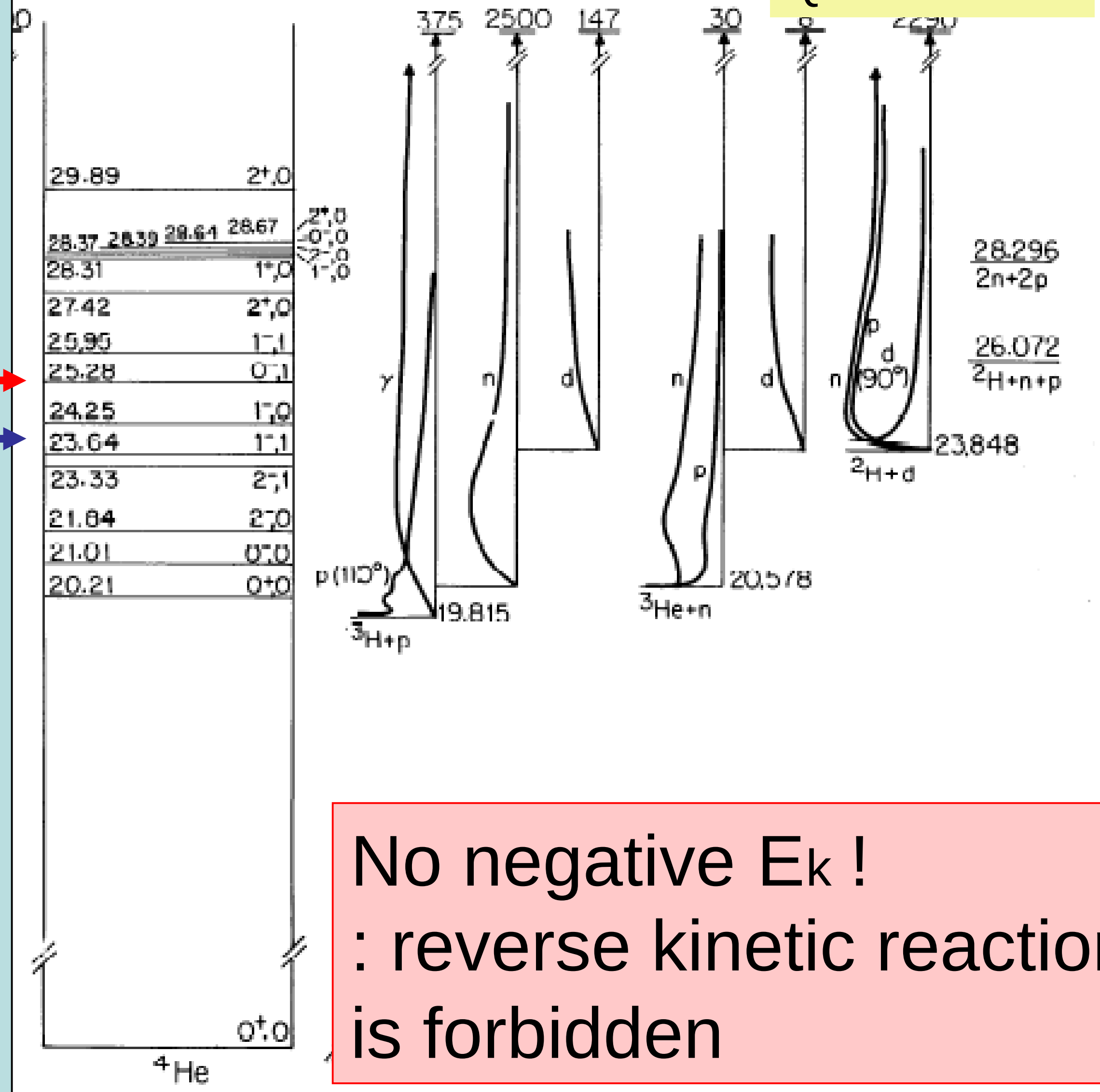
$d + d + E_k = {}^4He^*(E_x) = {}^4He^*(Q + E_k)$

Q = 23.8 MeV

Broad Resonance

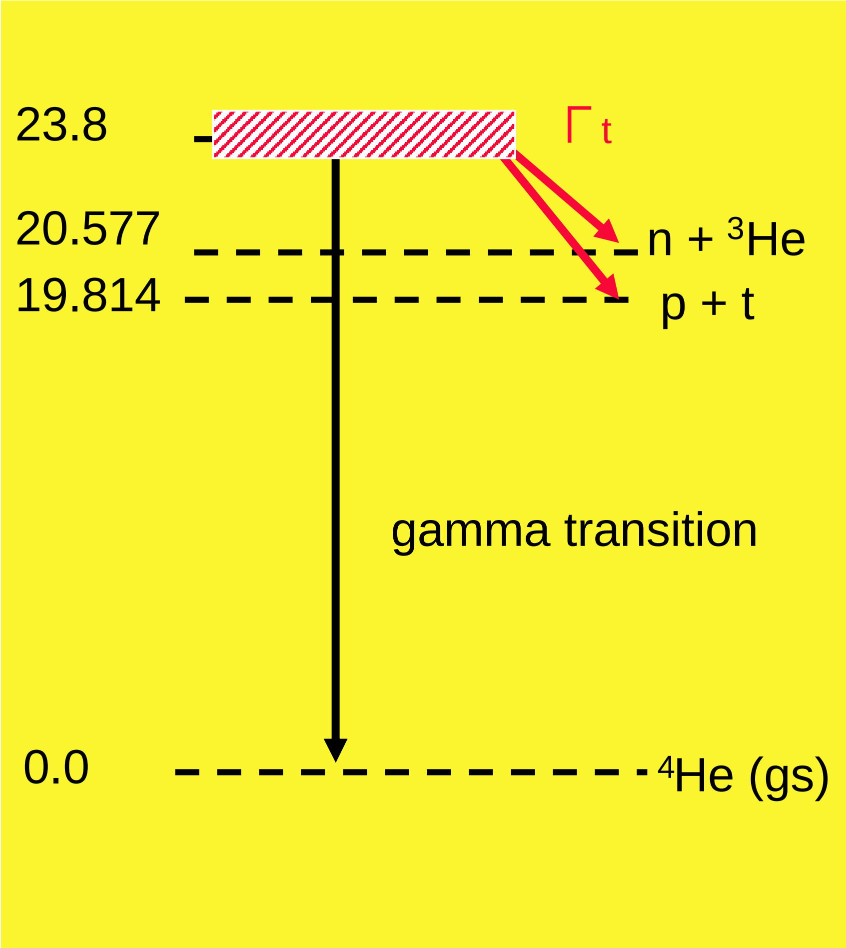
Ex = Q + 1.5MeV

Ex = Q + 0.025eV : CF?



No negative E_k !
: reverse kinetic reaction
is forbidden

d + d → ^{4}He*(23.8MeV) → Break-up



- Branching Ratio : $S_n(0)/S_p(0)/S_g(0) = \Gamma_n/\Gamma_p/\Gamma_g$ = 0.5/0.5/0.0000001 for E_k = 0 to 200 keV
- $\Gamma_n = \Gamma_p$ = 0.2 MeV
- Γ_g = 0.04 eV
- $\Gamma_t = \Gamma_n + \Gamma_p + \Gamma_g$
- $\tau = h/\Gamma_t$ = 1E−22 s
- $\tau_{gamma} = h/\Gamma_g$ = 1E−15 s

Scaling of PEF (Pion Exchange Force) for Nuclear Fusion

Two Body Interaction: PEF = 1

$n + \pi^{+} \rightarrow p$

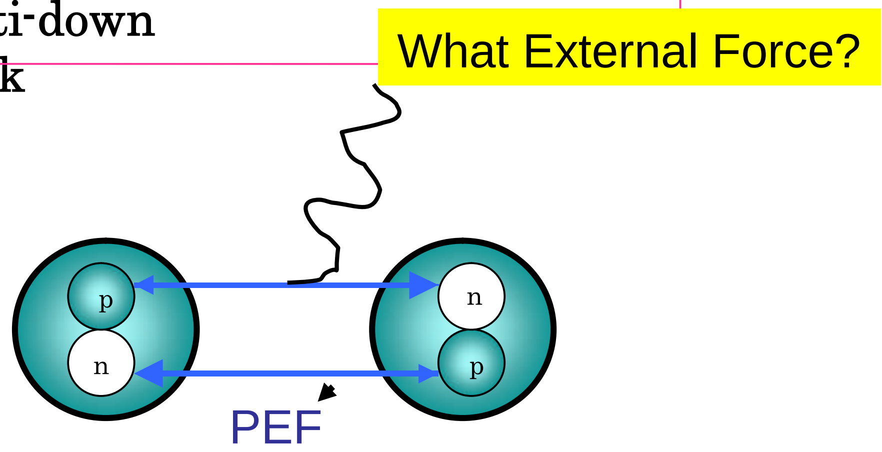
(udd) (ud*) (uud) : u ; up quark

$p + \pi^{-} \rightarrow n$:d ; down quark

(uud) (u*d) (udd) :u* ; anti-up quark

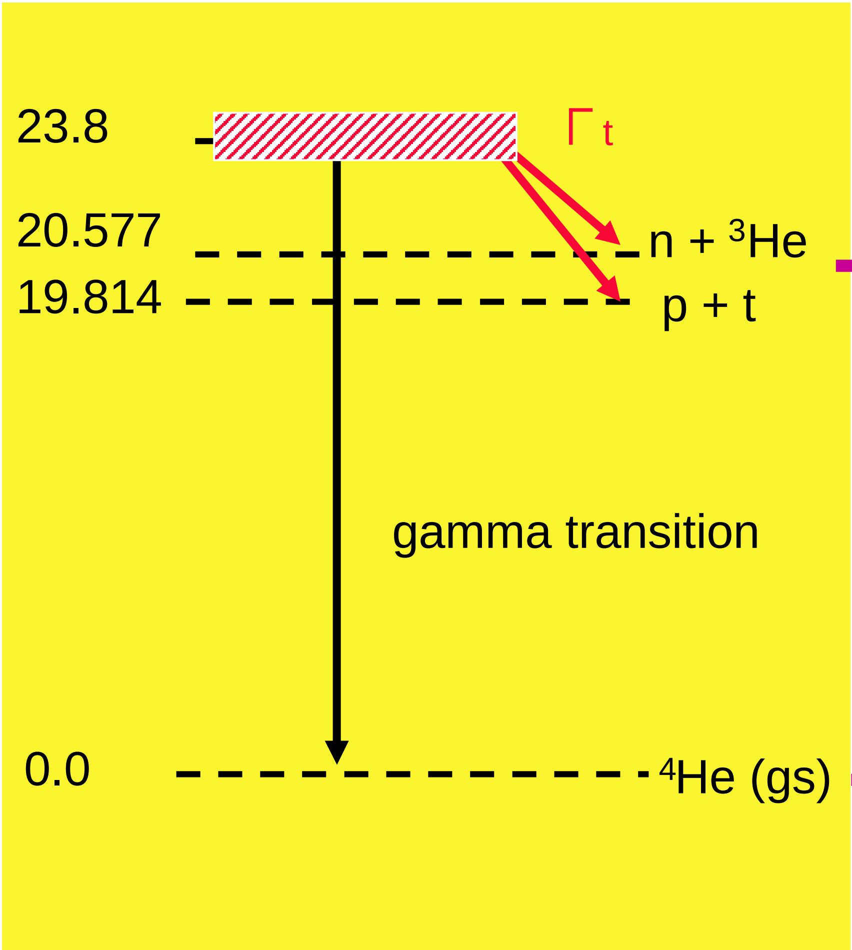
:d* ; anti-down quark

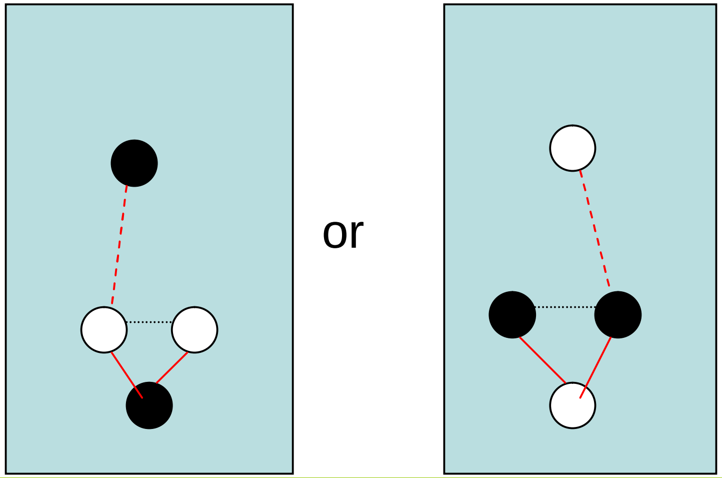
For D + D Fusion; PEF = 2



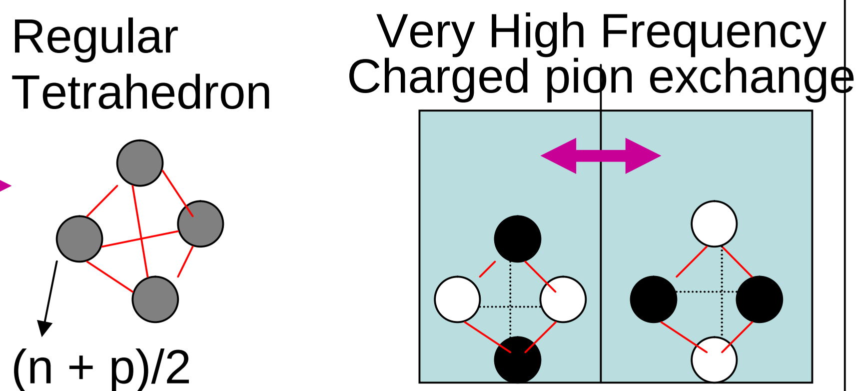
We need additional force in the initial state interaction, to change final state Branching Ratio and Products.

d + d → ^{4}He*(23.8MeV) → Break-up





Excited States break up to p + t or n + ^{3}He channels



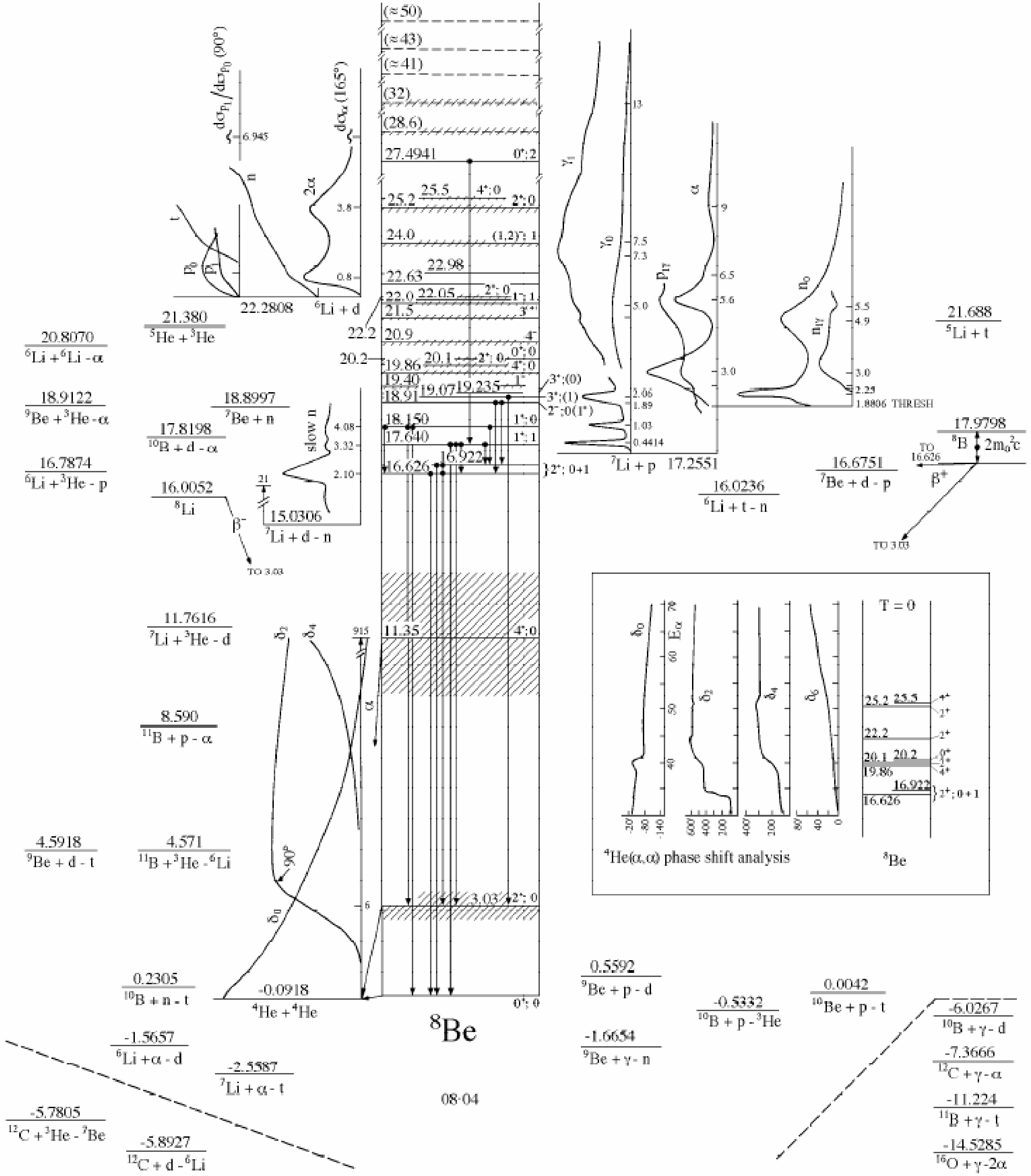
Bosonization by charged-pion exchange

Tetrahedron and Octahedron

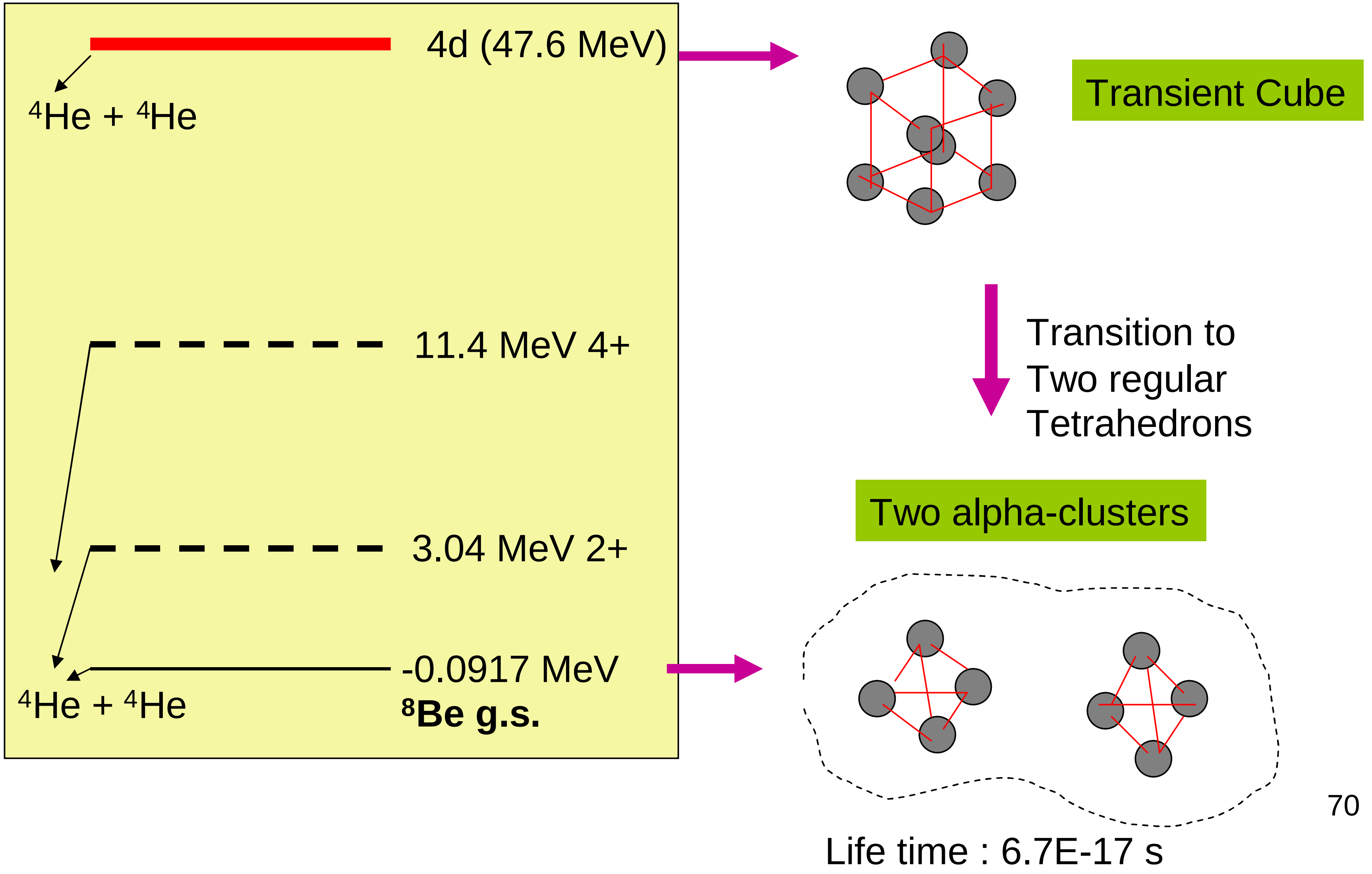
Regular Tetrahedral Arrangement

Regular Octahedral Arrangement

Energy Level Scheme of Be-8



$4D \rightarrow {}^4He + {}^4He + 47.6MeV$
(Final State Interaction)



Decay-Channel of ^{8}Be

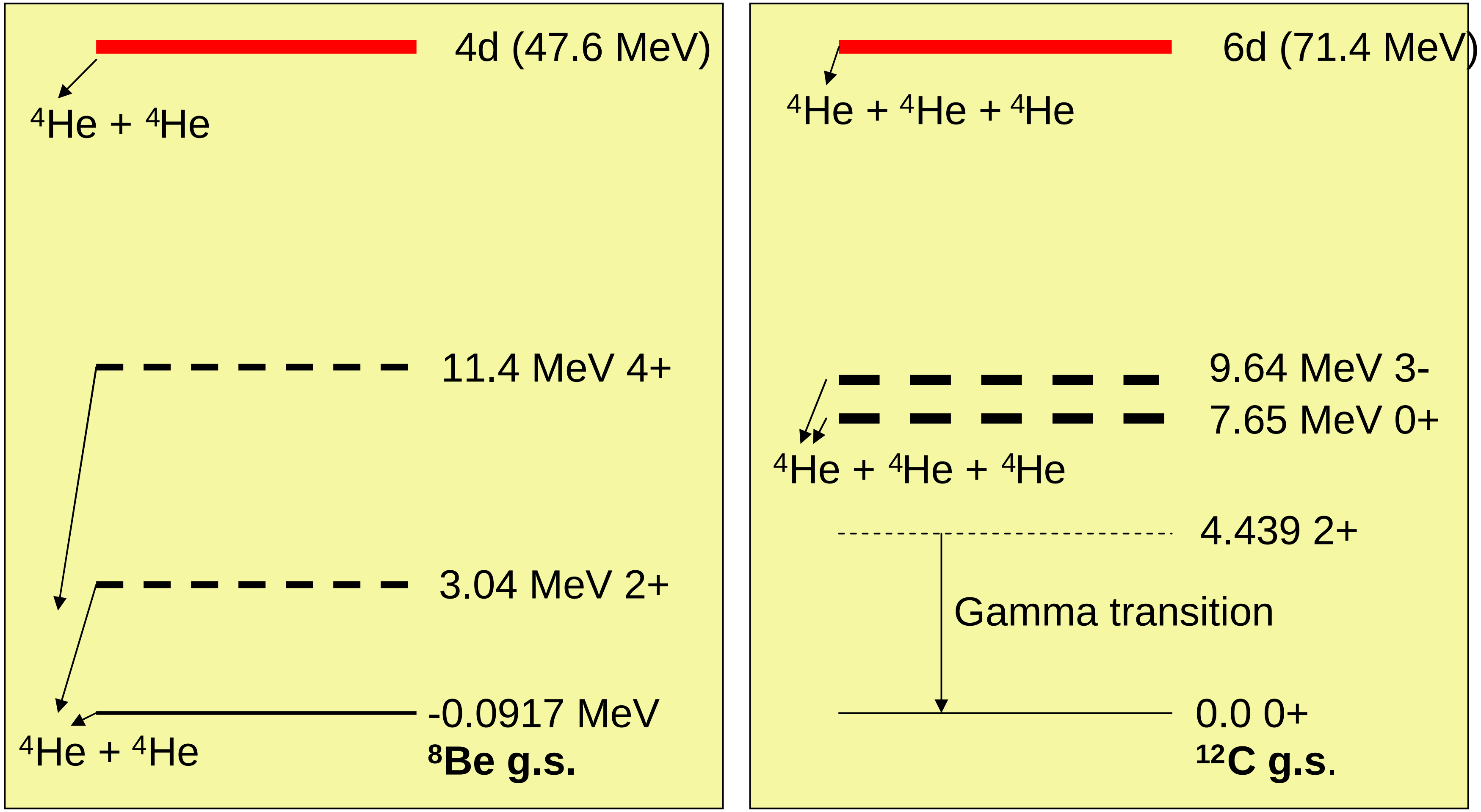
$4D \longrightarrow {}^{8}Be + 47.6\ MeV$:

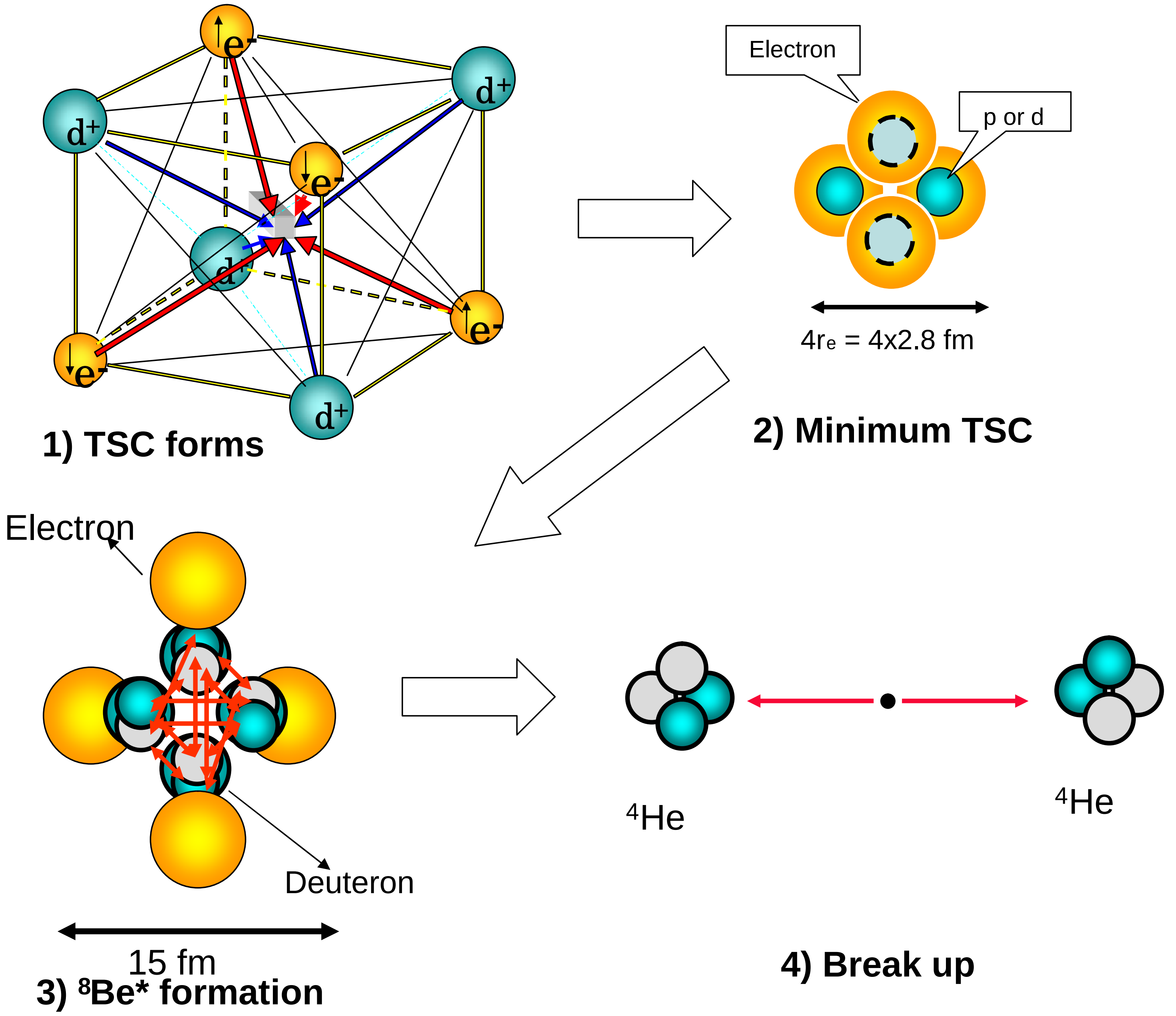
$^{8}Be \longrightarrow {}^{4}He + {}^{4}He + 91.86\ keV$: Major Ch.

- $\longrightarrow {}^{3}He + {}^{5}He(n+{}^{4}He) - 11.13\ MeV$
- $\longrightarrow t + {}^{5}Li(p+{}^{4}He) - 21.68 MeV$
- $\longrightarrow d + {}^{6}Li - 22.28\ MeV$
- $\longrightarrow p + {}^{7}Li - 17.26\ MeV$
- $\longrightarrow n + {}^{7}Be - 18.90\ MeV$

^{8}Be Excited State may open to threshold reactions

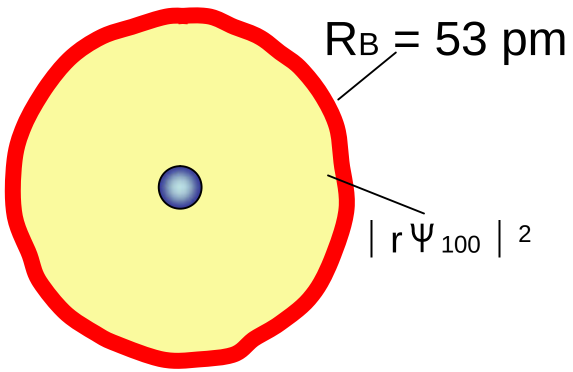
Branching Ratio
(Final State Interaction)



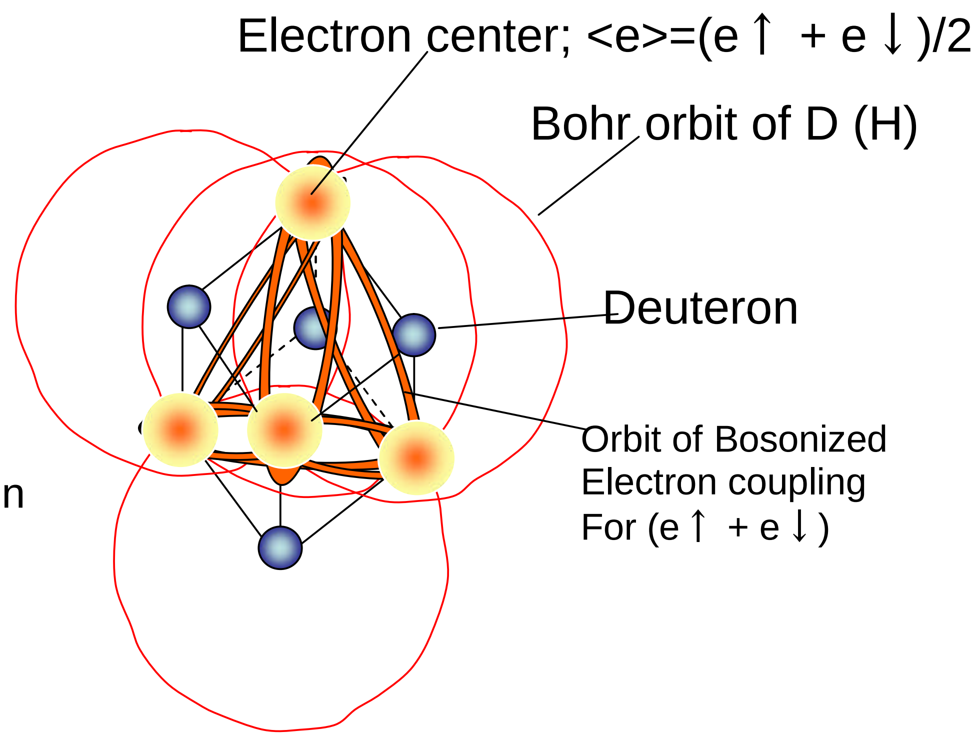


e-
d+
1) TSC forms
Electron
p or d
4re = 4x2.8 fm
2) Minimum TSC
Electron
Deuteron
15 fm
3) 8Be* formation
4He
4He
4) Break up

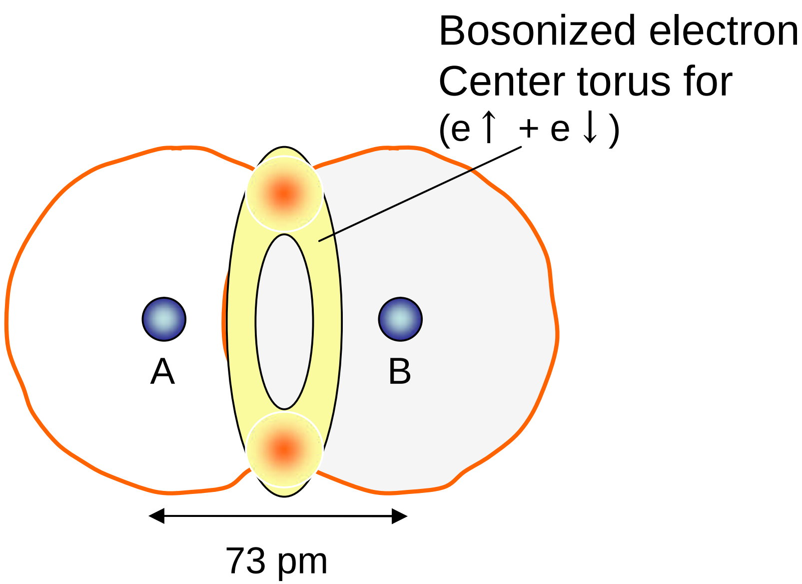
Feature of QM Electron Cloud



a) D atom (stable)



c) 4D/TSC (life time about 60 fs)



b) D_2 molecule (stable): $\Psi_{2D} = (2+2\Delta)^{-1/2}[\Psi_{100}(r_{A1})\ \Psi_{100}(r_{B2}) + \Psi_{100}(r_{A2})\ \Psi_{100}(r_{B1})]\,X_s(S1,S2)$

Wave Function for 4D/TSC (t=0)

- $\Psi_{4D} \sim \mathbf{a1}\,[\Psi_{100}(r_{A1})\ \Psi_{100}(r_{B2}) + \Psi_{100}(r_{A2})\ \Psi_{100}(r_{B1})]X_s(S1,S2)$
  $+\mathbf{a2}\,[\Psi_{100}(r_{A1})\ \Psi_{100}(r_{D4}) + \Psi_{100}(r_{A4})\ \Psi_{100}(r_{D1})]X_s(S1,S4)$
  $+\mathbf{a3}\,[\Psi_{100}(r_{A2})\ \Psi_{100}(r_{C4}) + \Psi_{100}(r_{A4})\ \Psi_{100}(r_{C2})]X_s(S2,S4)$
  $+\mathbf{a4}\,[\Psi_{100}(r_{B1})\ \Psi_{100}(r_{D3}) + \Psi_{100}(r_{B3})\ \Psi_{100}(r_{D1})]X_s(S1,S3)$
  $+\mathbf{a5}\,[\Psi_{100}(r_{B2})\ \Psi_{100}(r_{C3}) + \Psi_{100}(r_{B3})\ \Psi_{100}(r_{C2})]X_s(S2,S3)$
  $+\mathbf{a6}\,[\Psi_{100}(r_{C3})\ \Psi_{100}(r_{D4}) + \Psi_{100}(r_{C4})\ \Psi_{100}(r_{D3})]X_s(S3,S4)$

6-Bonds of “Bosonozed” electron-pairs (e↑ + e↓), which forms Regular Tetrahedron

4-Electron-Centers at Vertexes of Regular Tetrahedron

$u_{1s1}(r) = \Psi_{100}(r) = (1/\pi)^{1/2}(1/a_B)^{3/2}\exp(-r/a_B)$

Variational Principle

- $\delta\{<\Psi_{4D}|H|\Psi_{4D}>/<\Psi_{4D}|\Psi_{4D}>\} = 0$
  gives 6th order secular equation, not solvable.

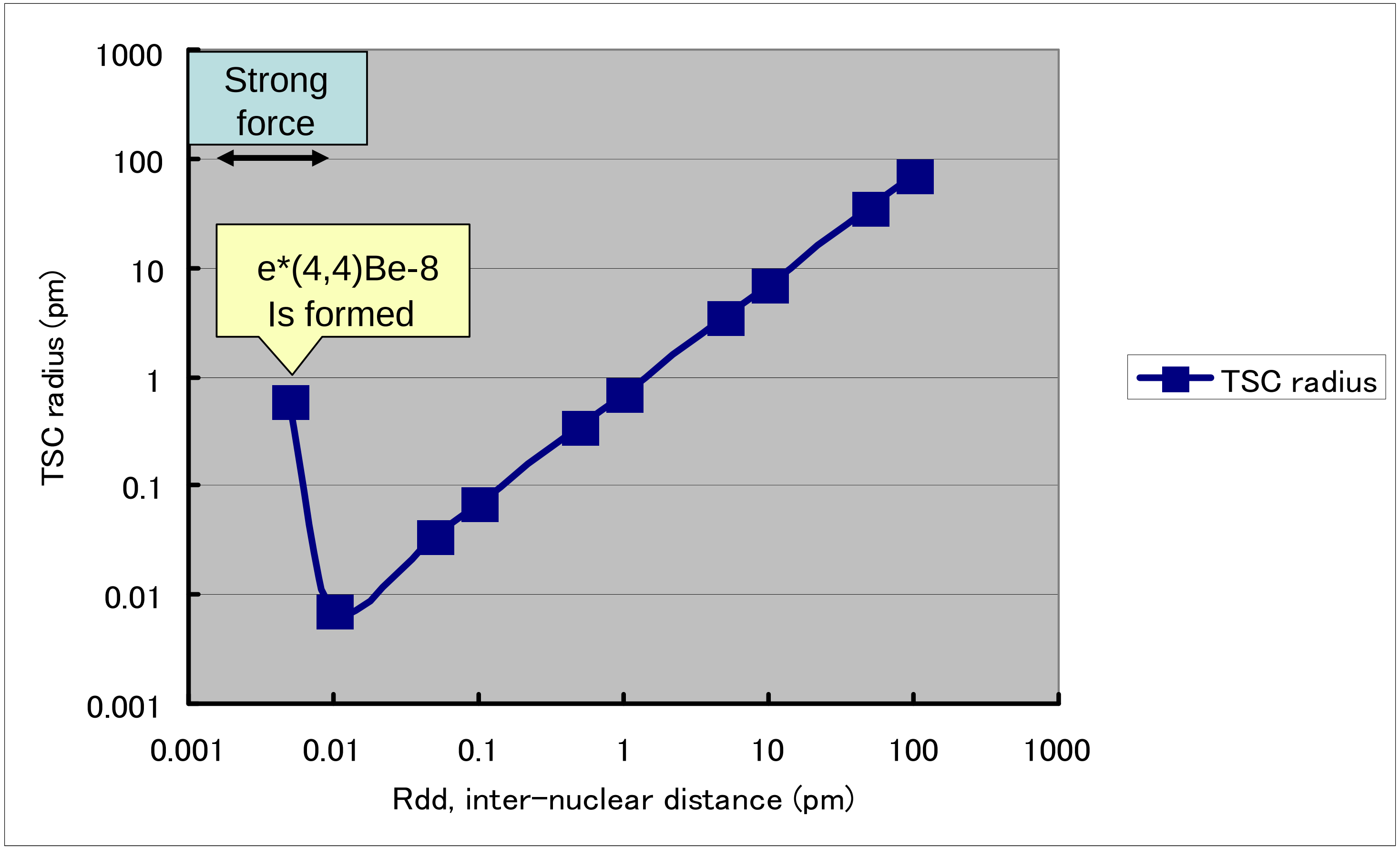
- But, under 3-dimensional symmetric constraint,
  we can set absolute values, a1 = a2 = a3 = a4 = a5 = a6 = a0,
  with $a0 = 1/(6(1+\Delta))^{1/2}$

- Orthogonal condition for 6 wing wave functions:

  aiaj = δ ij

TSC Size by Dynamic Condensation in about 60 fs motion

- Semi-Classical Treatment Possible -



$\langle r(t)\rangle = \langle r(0)\rangle - \langle v\rangle t$

$\langle r(0)\rangle = (3^{1/2}/2)R_B = 45.8$ pm

Basic Equations

- $\Psi_{4D}(r,t)$ **ai**

  $$= a_1(t)\ \Psi_{(1,1)}(r,t) + a_2(t)\ \Psi_{(2,2)}(r,t) + a_4(t)\ \Psi_{(4,4)}(r,t) \qquad (1)$$

- $<r(t)> = <r(0)> - <v>t$ (2)

- $<r(t)> = <\Psi^*_{4D}(r,t) \mathrm{I} r \mathrm{I}\ \Psi_{4D}(r,t)>$ (3)

Semi-Classical Approach

- $<r(0)> = (3^{1/2}/2)R_B = 45.8$ pm (4)
- Here, $R_B = 53$ pm (Bohr radius) (5)
- $<v> = v_0$; about 1E5 cm/s = 1 pm/fs (6)

- $<r(t)> = <r(0)> - v_0 t$ (7)

QM Approach

- $\Psi_{(1,1)}(r,t) = \Psi_{(1,1)}(<r(0)> - v_0 t)$ (8)
- $\Psi_{(2,2)}(r,t) = \Psi_{(2,2)}(<r(0)> - v_0 t)$ (9)
- $\Psi_{(4,4)}(r,t) = \Psi_{(4,4)}(<r(0)> - v_0 t)$ (10)

- At t = 0, TSC forms by two D_2 coupling
- $<r(0)> = (3/8)^{1/2} R_{dd}(0) = 0.61 R_{dd}(0)$ (11)
- $R_{dd}(0) = 73$ pm (12)

Time-Dependent Barrier Factor by Adiabatic Time-Dependent Potentials

- $R_{dd}(t) = R_{dd}(0) - v_0 t$ (13)
- Using $V_s(R_{dd})$ potential for dde*(m,Z) EQPET molecule, $R_{dd}(t)$ can be replaced with b value for Gamow integral
- And Time-dependent Gamow integral is defined and calculated.
- $$\Gamma(t) = 0.218 \int_{r0}^{b(t)} \sqrt{V_s(R_{dd}) - E_d}\, dR_{dd} \quad (14)$$

  in MeV, fm unit

Barrier Factor

- $b(t) = R_{dd}(t)$; for $V_s - E_d > 0$ (15)
- $= b(m,z)$; for $V_s - E_d < 0$ (16)
- Constraints:
- $b_{min} = b(2,2) = 4$ pm for $Z=1$
- $b_{min} = b(4,4) = 0.36$ pm for $Z=2$
- Barrier penetration probability for nD cluster is
- $P_{nd}(E_d,t) = \exp(-n\Gamma(t))$ (17)
- Numerical calculation is done by computer code programed

Time-Dependent Fusion Rate

- $\lambda_{nd(m,Z)}(t) = (S_{nd}v/E_d)P_{nd}(E_d,t)$ (18)
- $\lambda_{nd}(t) = a_1^2(t)\ \lambda_{nd(1,1)}(t) + a_2^2(t)\ \lambda_{nd(2,2)}(t)$
  $+ a_4^2(t)\ \lambda_{nd(4,4)}(t)$ (19)

With

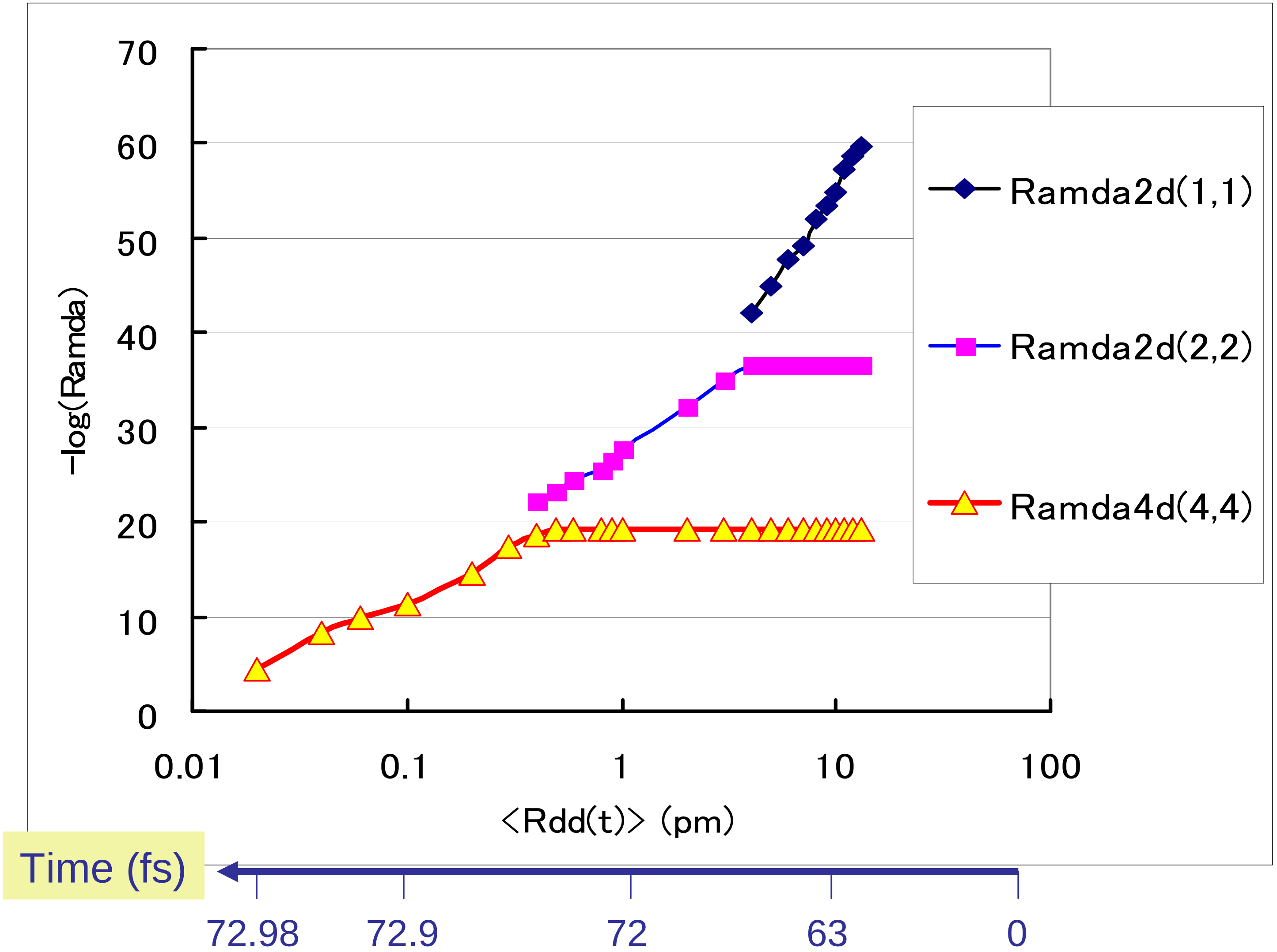
$a_1^2(t) = a_1^2(0) = 0.782$

$a_2^2(t) = a_2^2(0) = 0.187$

$a_4^2(t) = a_4^2(0) = 0.031$

Here combination-probabilities for parallel and anti-parallel spins of pairing electrons are only taken into consideration.

Time-Dependent EQPET Calculation for TSC
: Comparison of $\lambda_{2d(1,1)}(t)$, $\lambda_{2d(2,2)}(t)$ and $\lambda_{4d(4,4)}(t)$



TDEQPET Cal. For EQPET Molecules

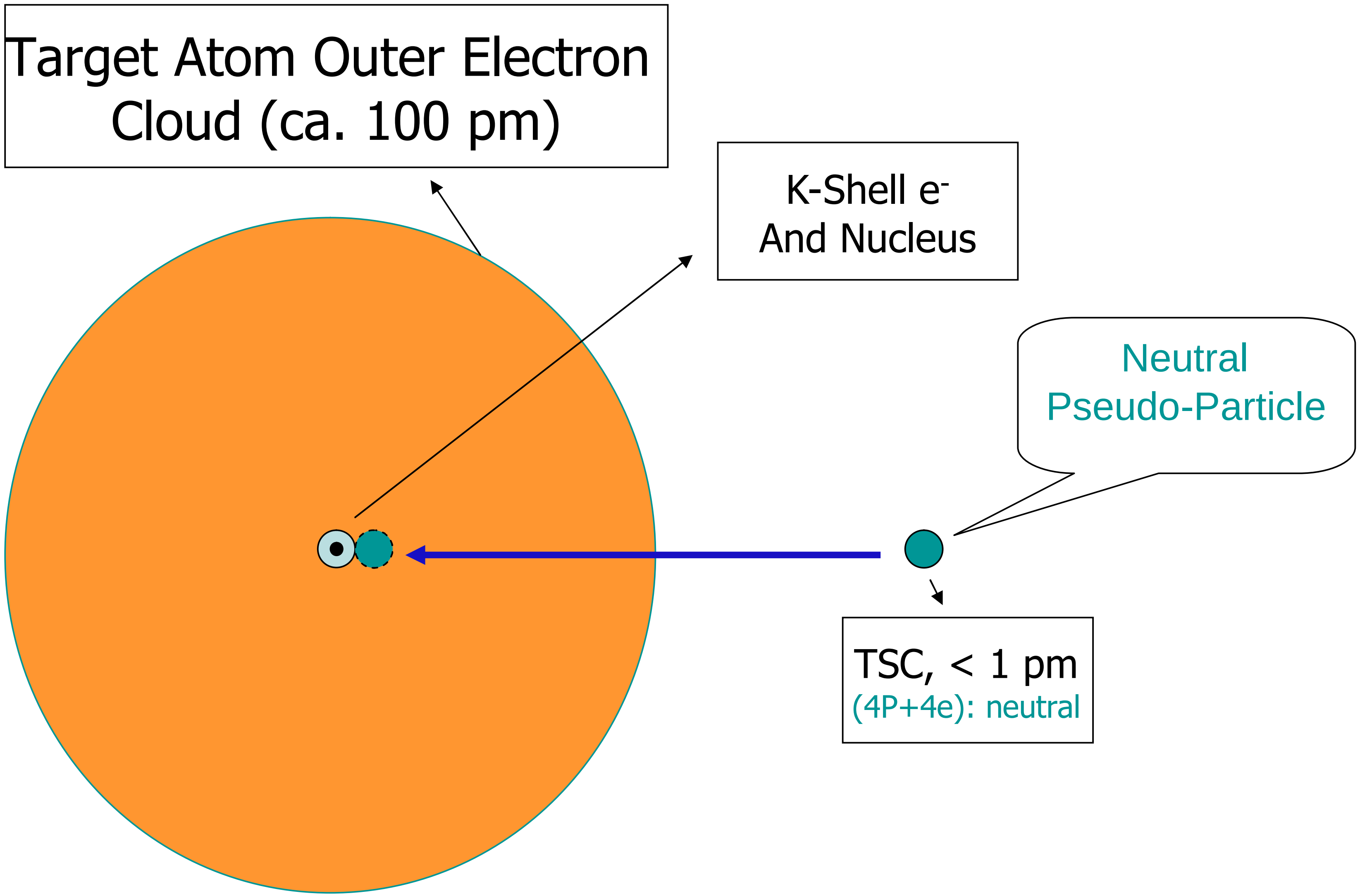
e*(m, Z)	< λ_{2d}> (f/s/cl.)	< λ_{4d}> (f/s/cl.)	$\lambda_{2d}(0)$ (f/s/cl.)	$\lambda_{4d}(0)$ (f/s/cl.)
(1, 1)	4.3E-44	7.8E-63	1.9E-60	7.3E-93
(2, 2)	2.9E-25	2.5E-24	2.4E-37	1.1E-50
(4, 4)	(2.1E-17)*	5.5E-8	(5.5E-22)*	5.9E-20

( )* : virtual value

Part-III:
TSC-Induced Nuclear Reactions

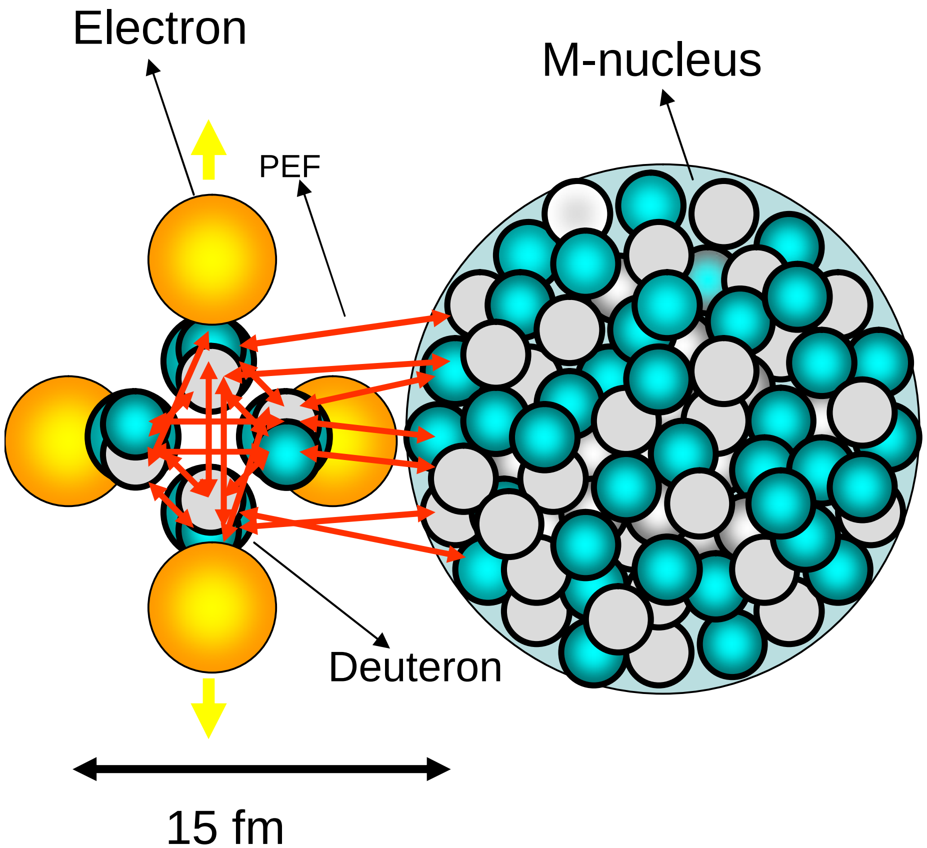
1) **Multi-Body Deuteron (d-p mixed) Self-Fusion within TSC**;
   2d, dp, 3d, ddp, 4d, dddp, dpdp
   ; **EQPET Model Alanysis**

2) **TSC+Host-Metal Reactions**;
   Sudden Tall Thin Barrier Approximation
   (**STTBA**)



•How deep can TSC penetrate through e-cloud?

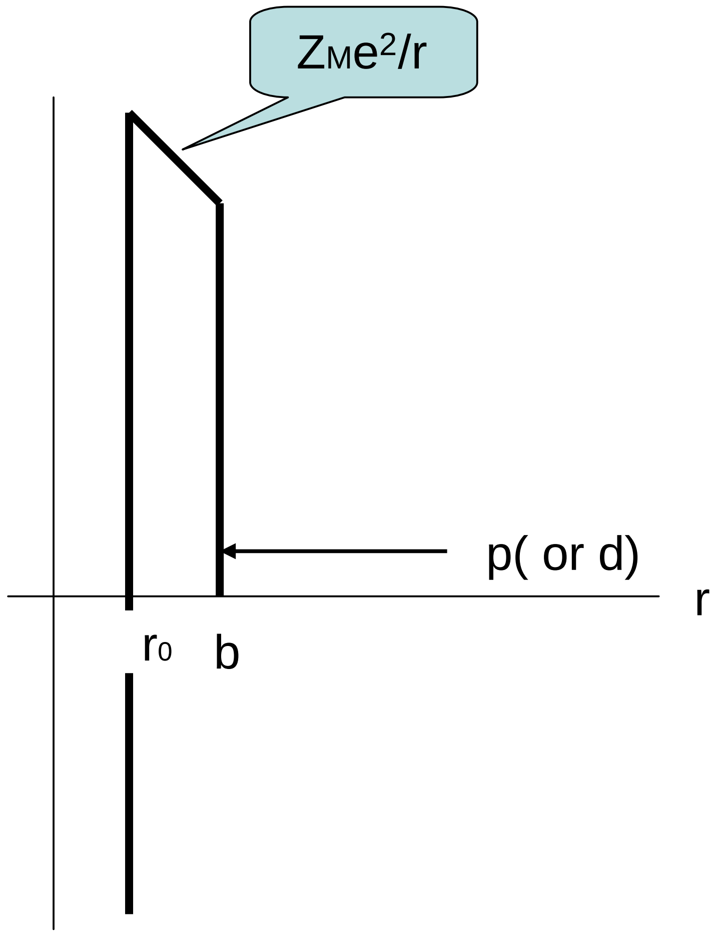
M + 4d/TSC
Nuclear Interaction Mechanism



- Over-minimum sate of 4d/TSC
- Admixture of 4d/TSC to form $^{8}Be^{*}$
- M + $^{8}Be^{*}$ capture reaction
- Strong force exchange (PEF) between M and $^{8}Be^{*}$

Sudden Tall Thin Barrier Approx.

When p (or d) gets into the strong force range, electrons separate and p (or d) feel Coulomb repulsion to the M-nucleus charge



- $r_0 = 1.2A^{1/3}$
- $b = r_0 + \lambda_\pi (=2.2 \text{ fm})$
- $P_M(E) = \exp(-G)$
- $G = 0.436(\mu V(R_{1/2}))^{1/2}(b - r_0)$
- $R_{1/2} = r_0 + (b - r_0)/2$
- Reaction rate:

  $\lambda = S_{Mp}(E)vP_M(E)P_n/E$
- $P_n =$

  $\exp(-0.218n(\mu V_{pp})^{1/2}R_{pp})$

  : Plural p (or d) existence probability in λ_π range for n > 1. $P_n = 1$, for n = 1.

Results by STTBA calculation; M = Ni

- $P_{Mp}(E) = 9.2E-2$
- $P_{Md}(E) = 3.5E-2$

Reaction Rates:

- $\lambda_{Mp} = 3.7E-8$ (f/s/pair)
- $\lambda_{Md} = 2.1E-7$ (f/s/pair)
- $\lambda_{M4p} = 1.0E-8$ (f/s/pair)
- $\lambda_{M4d} = 3.4E-9$ (f/s/pair)
- <Macroscopic Reaction Rate> = $\lambda \times N_{M+TSC}$
- With N_{M+tsc} = 1.0E+16 in 10nm area, Rate = 1E+8 f/s/cm2 and Y = 1E+14 in 1E+6 sec.

$V_{pp} = 1.44/6 = 0.24$ MeV
$P_{2p} = 0.527$
$P_{2d} = 0.404$

$S_{Mp}(0) = 1.0E+8$ kevb
$S_{Md}(0) = 1.0E+9$ keVb

$\lambda_{4d} = 4.9E-5$

STTBA Prediction for Cs-to-Pr

- S_{Mp} = 1E+8 kevb
- S_{Md} = 1E+9 keVb
- λ_{Mp} = 8.4E-10 f/s/tsc
- λ_{M4p} = 2.3E-10 f/s/tsc
- λ_{Md} = 2.8E-8 f/s/tsc
- λ_{M4d} = 7.6E-9 f/s/tsc
- Where combination probability of anti-parallel spin was used for 4p/TSC.

- Suppose N_{M+tsc} = 1E+17 in 10 nm layer of surface
- Macro Yield = λ xN_{tsc} = 7.6E-9 x 1E+17

  = 7.6E+8 (f/s/cm^2)
- Cs-to-Pr rate =

  4.6E+14 (atoms per week)

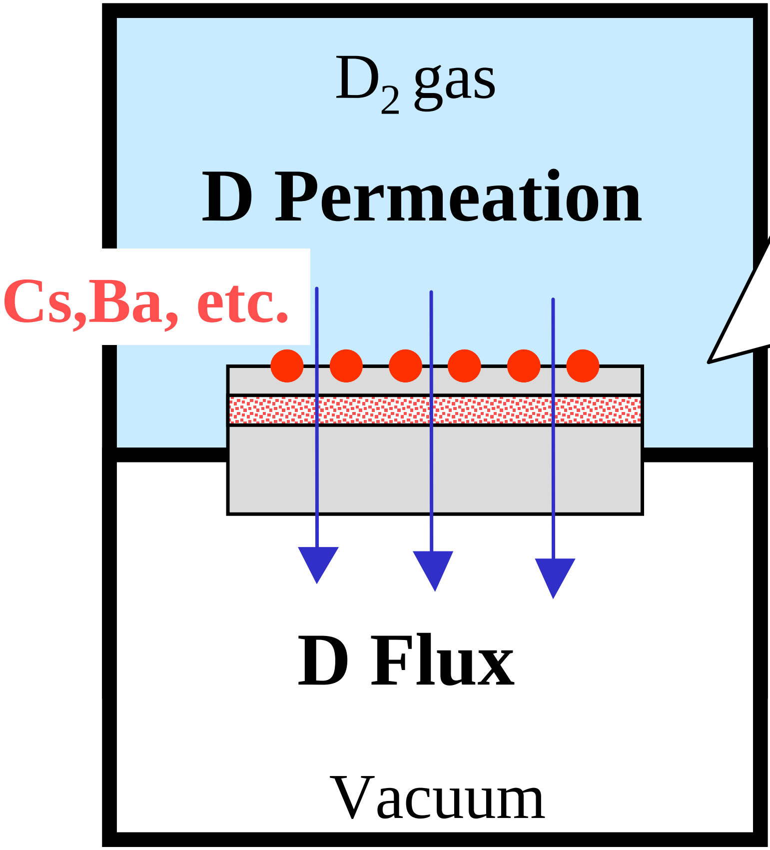
  per cm^2

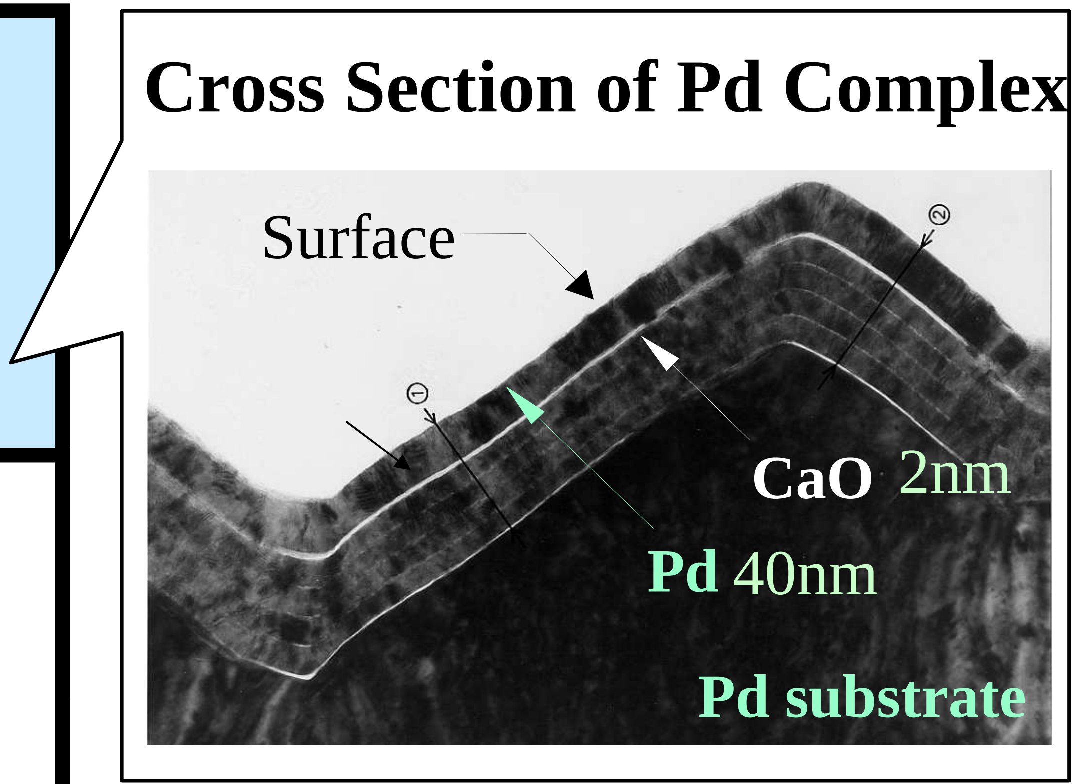
We see good agreement with Iwamura experiment.

Features of the Present Method

After Iwamura, et al

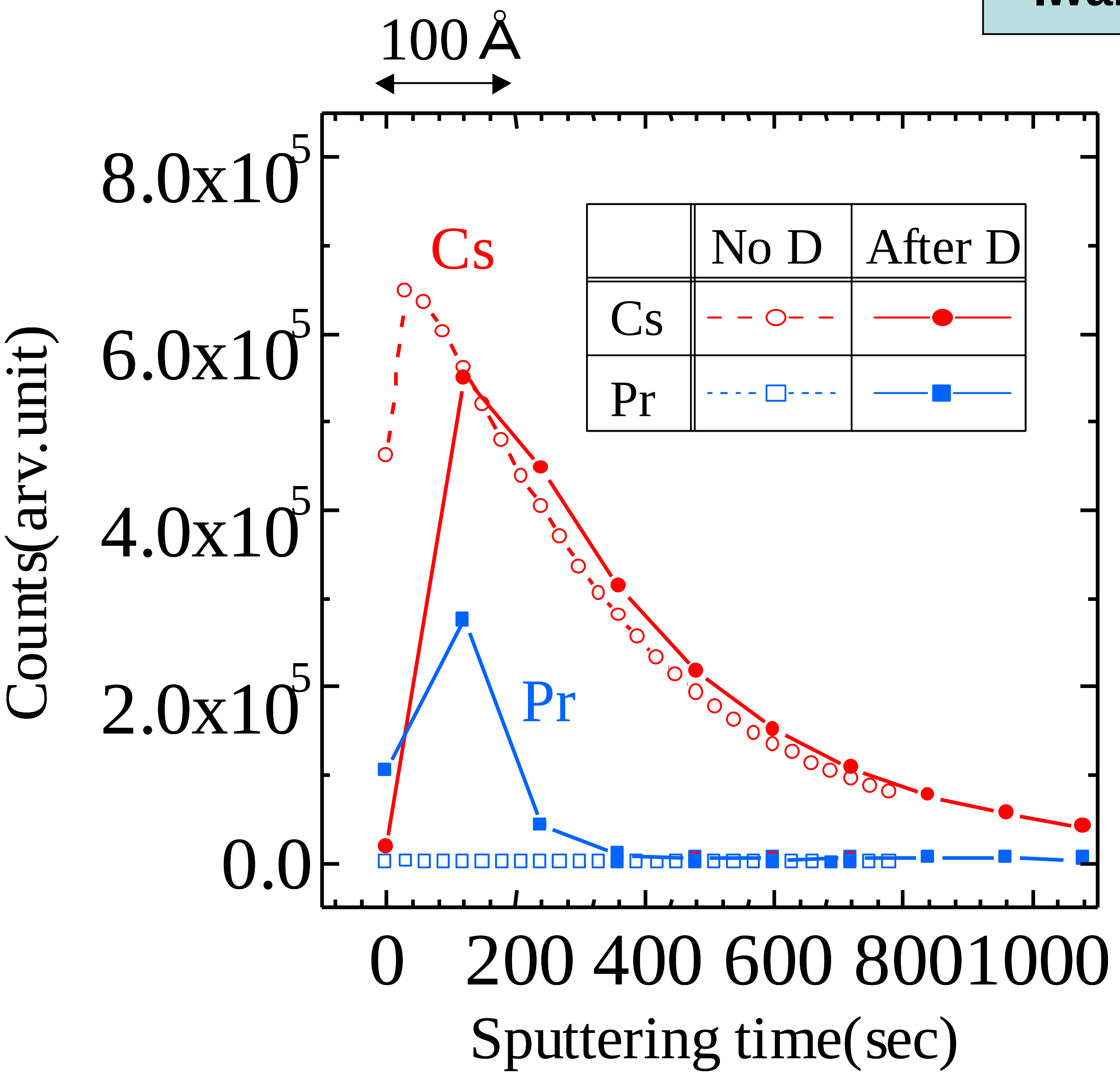
D_2 gas permeation through the Pd complex





Depth Profile of Cs and Pr by TOF-SIMS

Iwamura: ICCF11



Where is the Pd+4d/TSC reaction taking place?

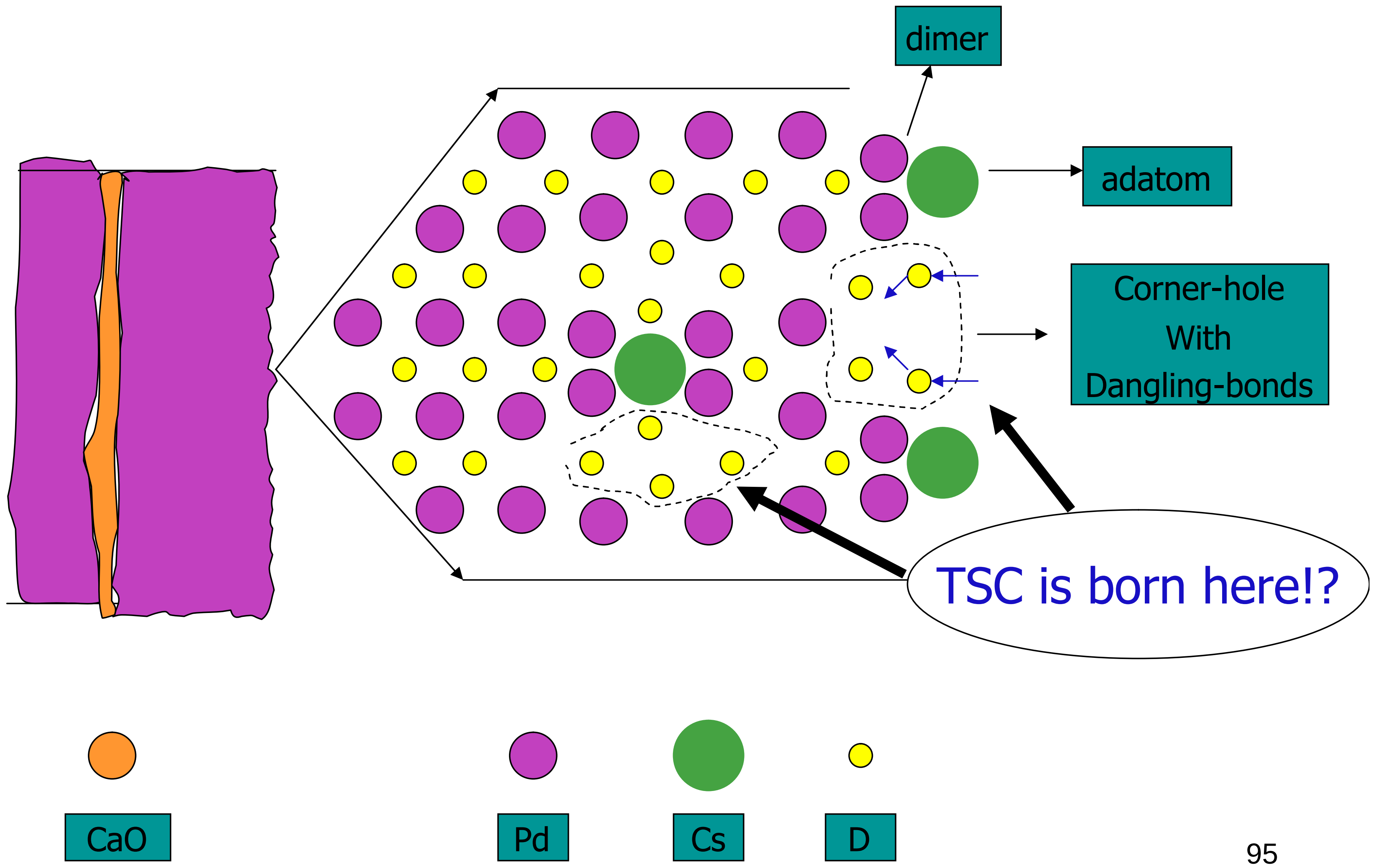
1) Pr is seen in 0-30 nm from surface.

2) CaO/Pd boundary is at r=40 nm, where e*(2,2) may be born by free electron in Fermi-gap.

<Q> Why ca. 25 nm gap (40-15) is seen?

<A> Pr is produced by Cs + 4d/TSC at the boundary and diffuses to the surface?

Image of Surface



Role of CaO/Pd Interface

1) CaO layer as blocking layer of D-diffusion: to enhance D/Pd in Pd region, but to be half-transparent for D-flux (current by permeation)
2) Fermi-gap at CaO/Pd Interface: to emit free electrons from CaO zone into conduction band of Pd zone and to generate transient Cooper pairs, e*(2,2). This leads to formation of dde*(2,2) quasi-molecules and finally 4d/TSC by coupling of two dde*(2,2)'s.

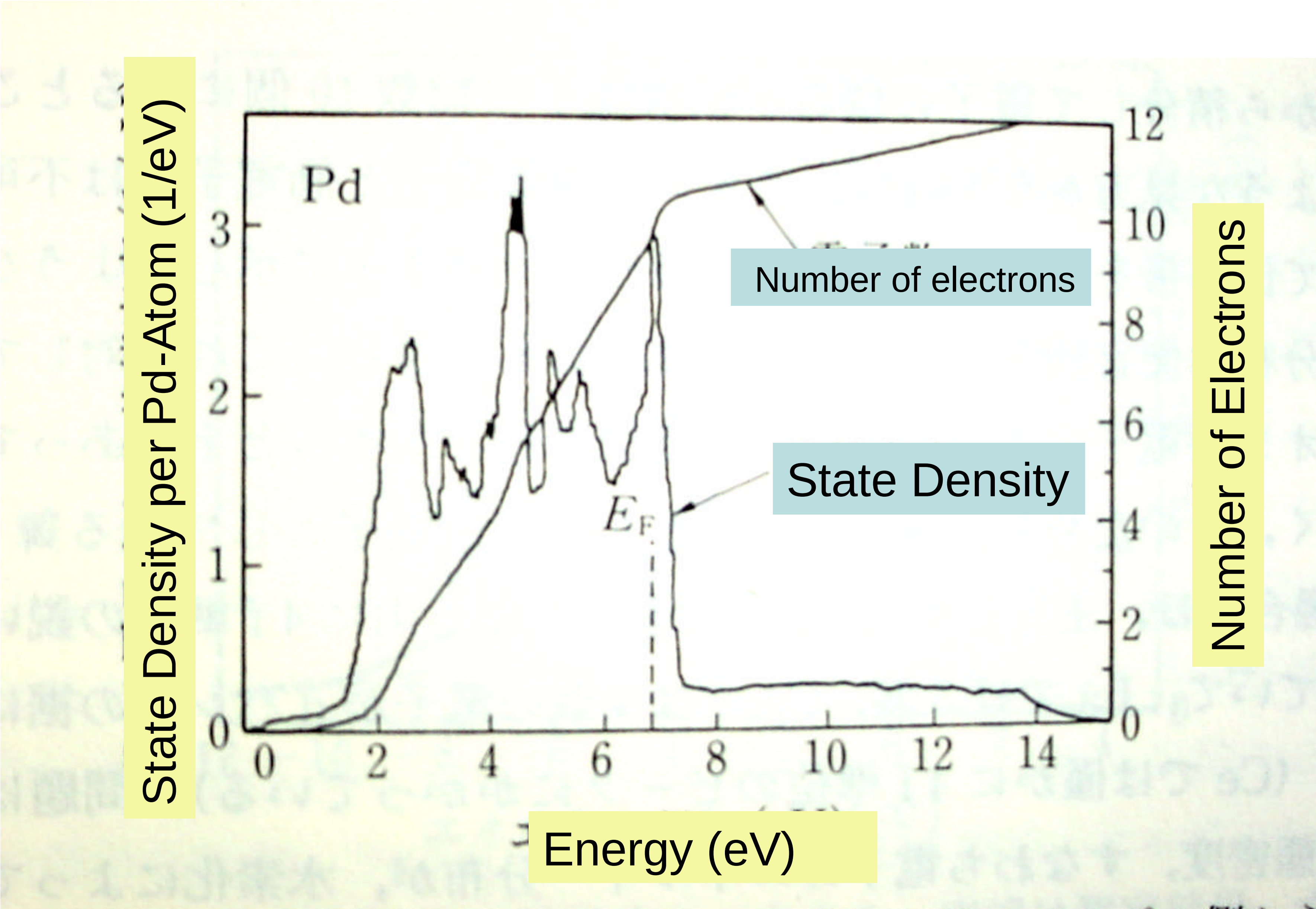
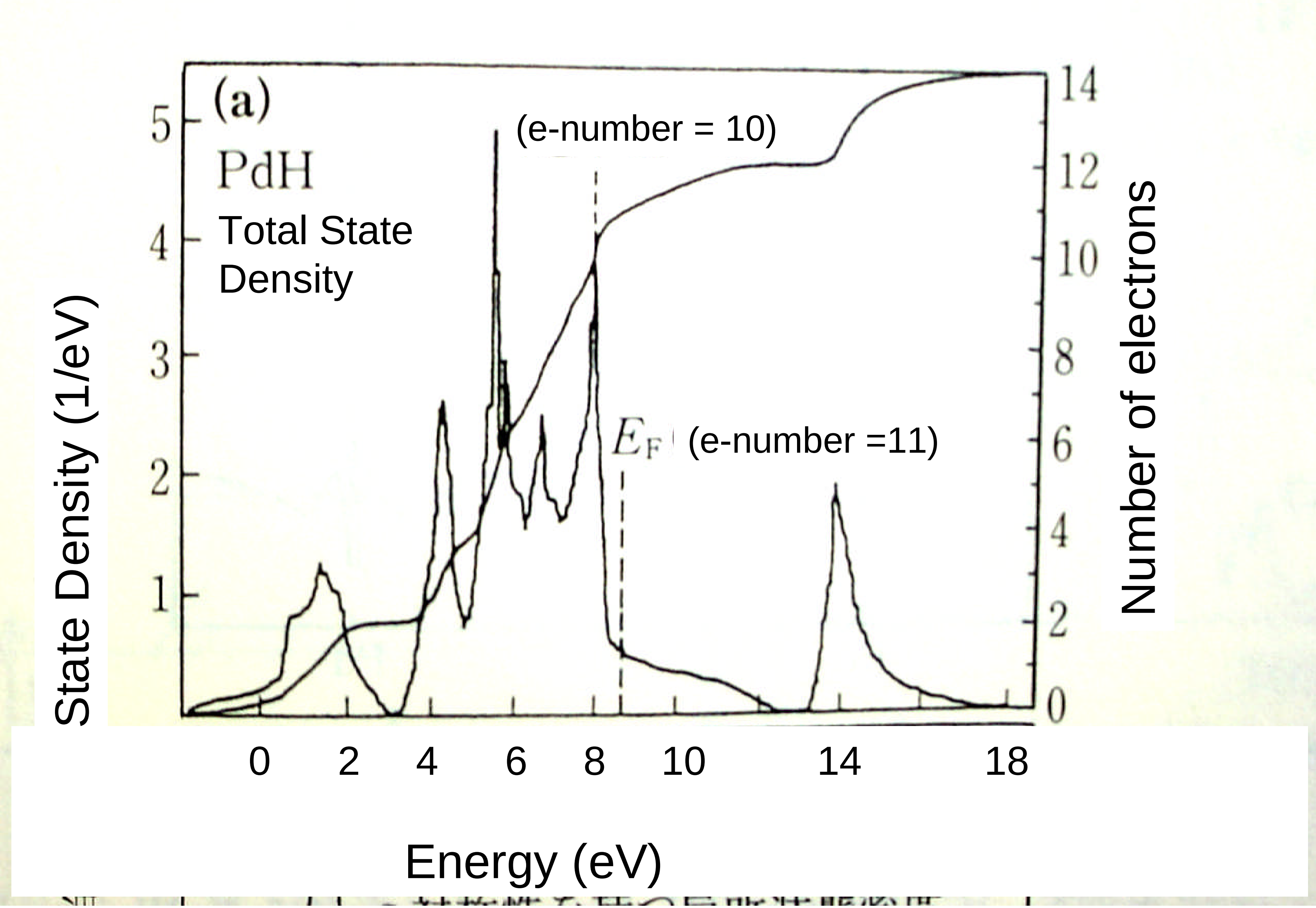
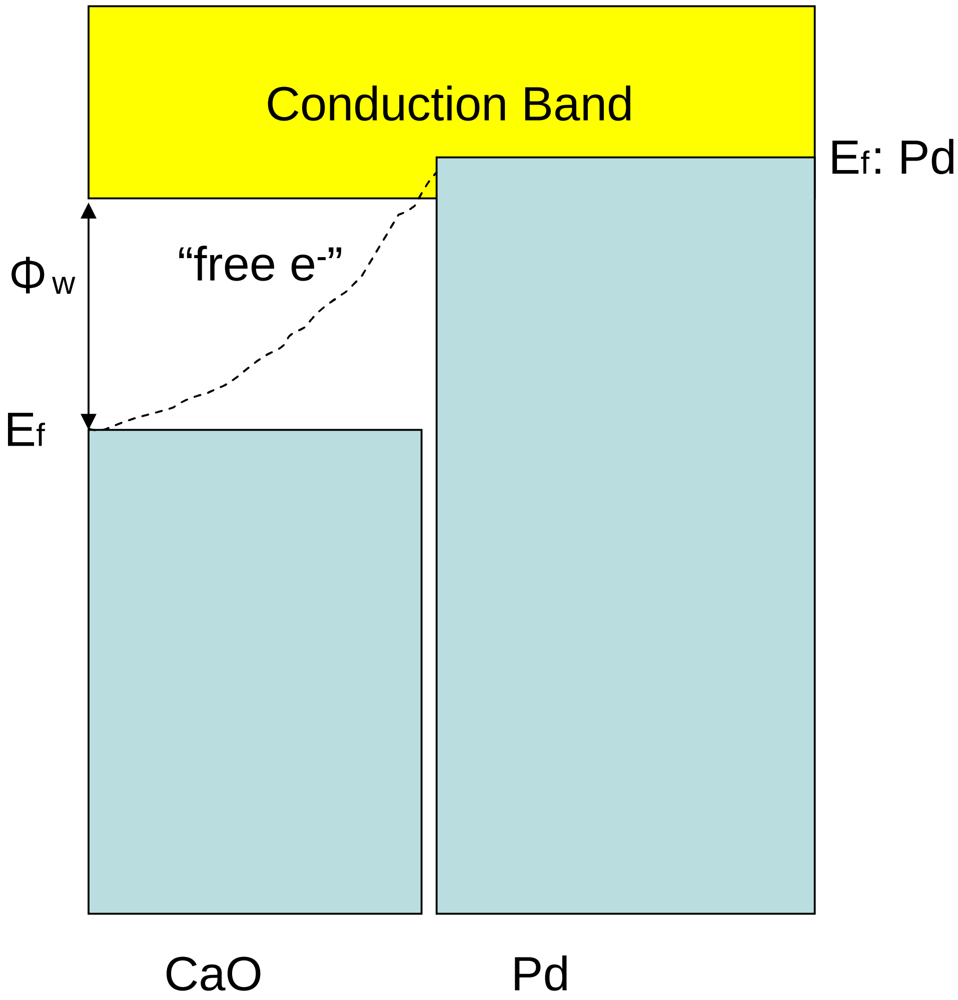


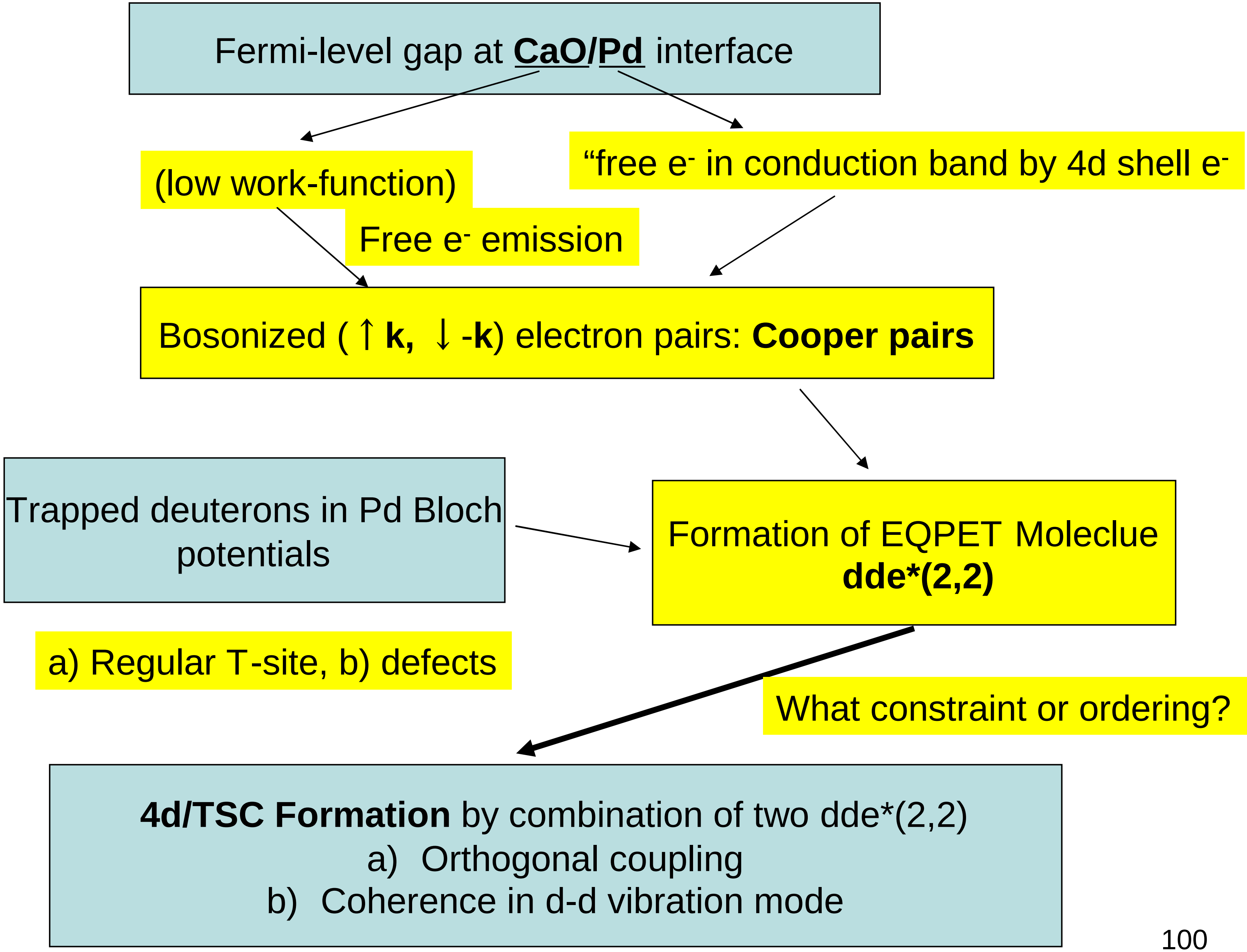
Fig. : Calculated electron density for Pd metal (by Y. Fukai)

Electron Sates in PdH (by Y. Fukai, 1998)



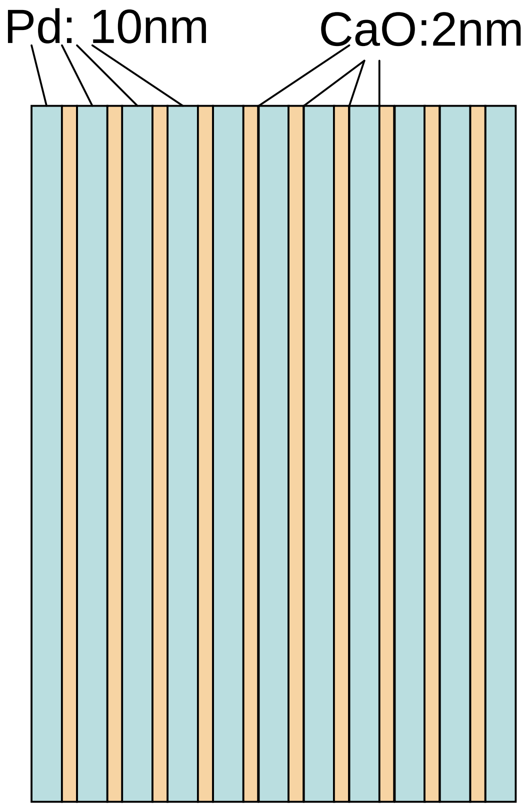
Fermi-Level Gap at CaO/Pd Interface



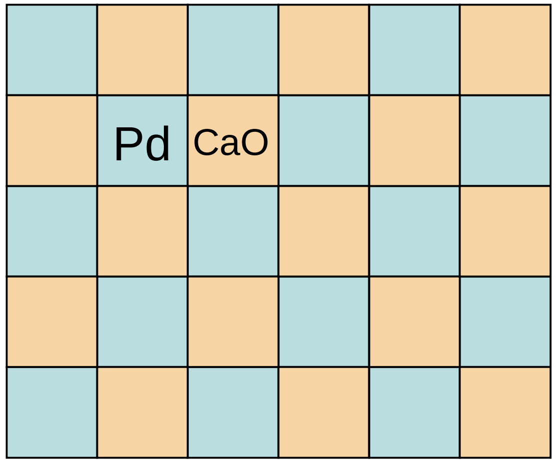

Fermi-level gap at **CaO/Pd** interface
(low work-function)
"free e- in conduction band by 4d shell e-
Free e- emission
Bosonized (↑ **k**, ↓ -**k**) electron pairs: **Cooper pairs**
Trapped deuterons in Pd Bloch potentials
Formation of EQPET Moleclue **dde*(2,2)**
a) Regular T-site, b) defects
What constraint or ordering?
4d/TSC Formation by combination of two dde*(2,2)
a) Orthogonal coupling
b) Coherence in d-d vibration mode

Interesting Pd/CaO Lattices

- Periodical Layers



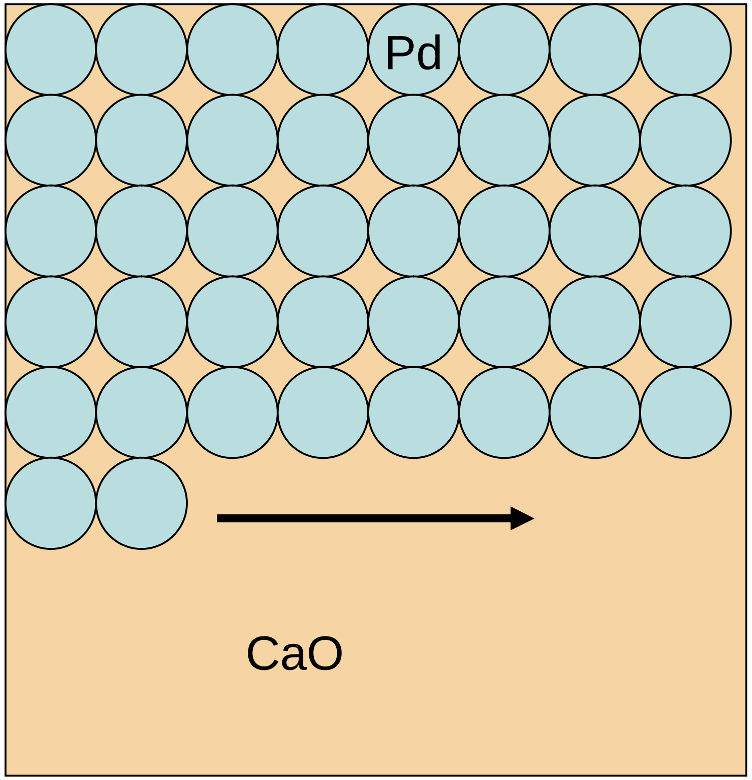
- Grid



5nmx5nm per unit

Fabrication of Pd/CaO Cluster

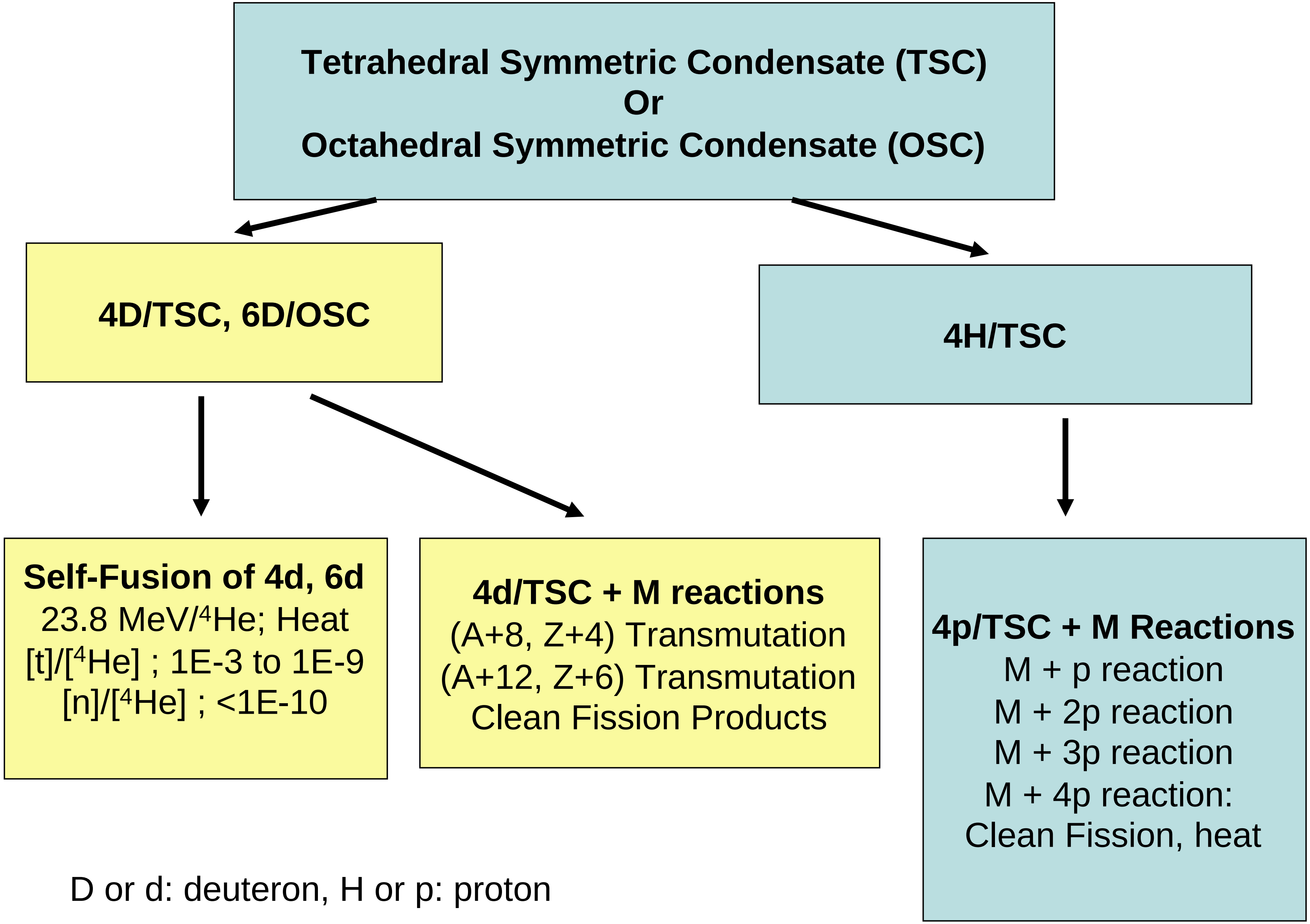
- Structure



- CaO pool
- 5nm diam Pd wires
- Put Pd wires in CaO pool
- Bundle and fix Pd wires
- Pd/CaO Hetero Lattice for Cathode

Major Results: Experiments vs. Theory

Item	Experiment Author/ Method/ Results	EQPET/TSC Model
Screening of d-d	Kasagi/beam/310eV Takahashi/3D/1E+9 <dd>	360eV by dde*(2,2) (1E+13) τ (0.1ms)
^{4}He Production	McKubre/Electrolysis/ 30+-13MeV/^{4}He	23.8MeV/^{4}He by 4D → ^{4}Hex2 +47.6MeV
Maximum Heat	El Boher/El./24.8keV/Pd Gain ≈ 25	23 keV/Pd 46MeV/cc by 4d/TSC
Transmutation	Iwamura/Perm./Cs→Pr Miley/NiH/Fission-like Pro.	4d/TSC + M 4p/TSC + M reaction



D or d: deuteron, H or p: proton