Influence of Chaos on the Fusion Enhancement by Electron Screening

Sachie Kimura and Aldo Bonasera

Laboratorio Nazionale del Sud, INFN

Italy

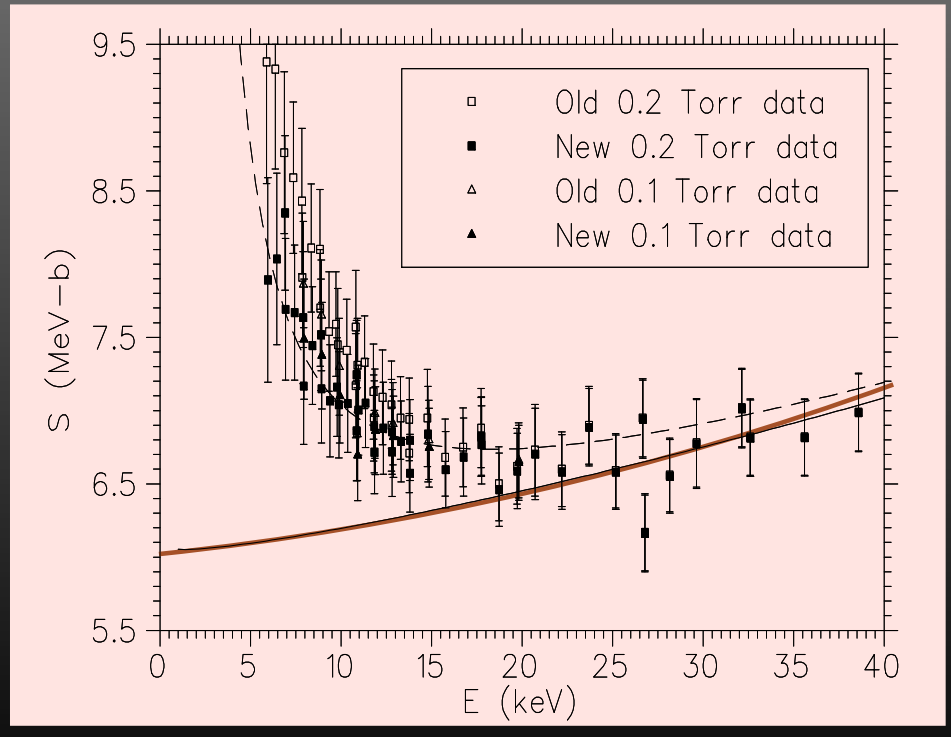
Quantum Tunneling and Chaos

Tunneling: Quantum phenomenon
however,
strongly Influenced by Classical Chaos

Chaos induces Large Fluctuations of classical action around mean value
$\Rightarrow$ Large Fluctuations of Tunneling Period
(Chaos-assisted Tunneling)

Large Enhancement

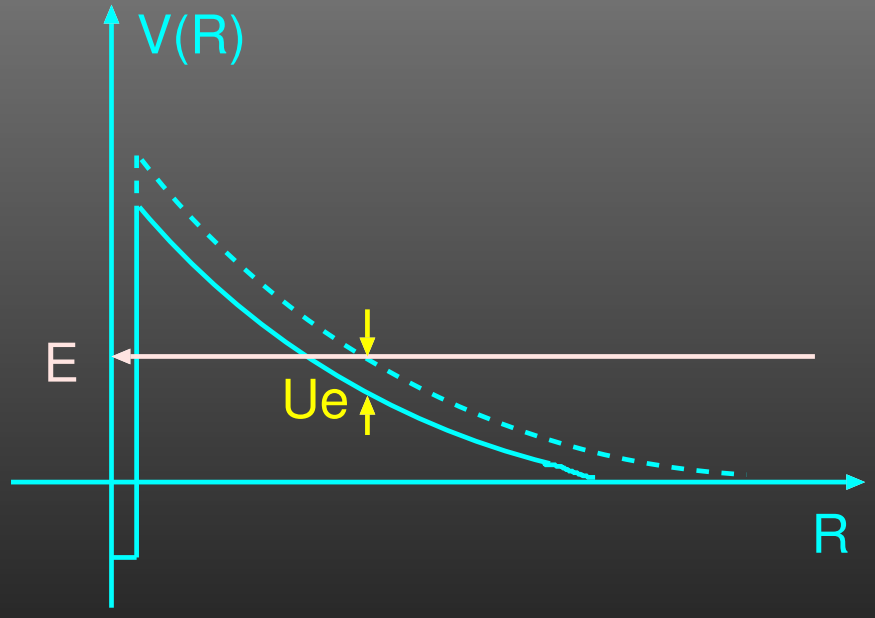
^{3}He(d,p)^{4}He



Ref. K. Langanke *et al.*, Phys. Lett. B 369,211(1996)

Energy loss, electron screening and the astrophysical ^{3}He(d,p)^{4}He cross section

Screening Energy



$$f_e \equiv \frac{\sigma(E)}{\sigma_0(E)} = \frac{\sigma_0(E+U_e)}{\sigma_0(E)}$$

$$\sim \exp\{\pi\eta(E)\frac{U_e}{E}\}$$

$$U_e \sim \frac{E}{\pi\eta(E)}\log f$$

U_e : Screening Energy

Screening potential

Reaction	U_e [eV]		
	AD. app.	Ref.[1]	THM
D(d.p)T	20	8.7(Quadratic)	
		7.3(Cubic)	
^{3}He(d,p)^{4}He	119	34(Quadratic)	180$\pm$40
		60(R-matrix)	
		200(R-matrix)	
^{6}Li(d,α)^{4}He	175	259(Cubic)	320$\pm$50
		248($R-$matrix)	
^{7}Li(p,α)^{4}He	175	134(Cubic)	330$\pm$40
		204(Cubic)	
		155(R-matrix)	
		242(R-matrix)	

[1] F. C. Barker, Nucl. Phys. A **707**,277(2002)

Problem has not been settled yet

Aim of the Study

- Determination of the effect of screening by bound electrons in many electrons system (D+d,^{3}He+d, ^{6}Li+d)

Aim of the Study

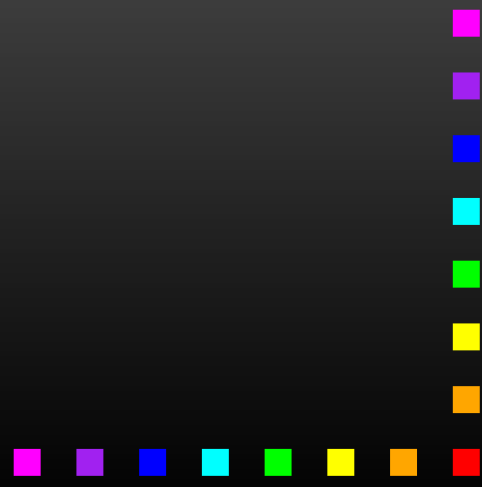
- Determination of the effect of screening by bound electrons in many electrons system (D+d,^{3}He+d, ^{6}Li+d)
- Effect of electron capture into the k-shell of the projectile. (D+D, ^{3}He+D, ^{6}Li+D)

Aim of the Study

- Determination of the effect of screening by bound electrons in many electrons system (D+d,^{3}He+d, ^{6}Li+d)
- Effect of electron capture into the k-shell of the projectile. (D+D, ^{3}He+D, ^{6}Li+D)
- Investigation in very low energy region (fluctuation plays a key role, beyond TDHF)

Aim of the Study

- Determination of the effect of screening by bound electrons in many electrons system (D+d,^{3}He+d, ^{6}Li+d)
- Effect of electron capture into the k-shell of the projectile. (D+D, ^{3}He+D, ^{6}Li+D)
- Investigation in very low energy region (fluctuation plays a key role, beyond TDHF)
- Seek the relation between Quantum Tunneling and Chaos



Constrained Molecular Dynamics (CoMD)

S.Kimura and A.Bonasera, physics/0409008, Phys. Rev. A in press

Lagrange multiplier method for constraints

$$\mathcal{L} = \sum_i \frac{\mathbf{p}_i^2}{2m_i} - \sum_{i,j(\neq i)} U(\mathbf{r}_{ij}) + \sum_{i,j(\neq i)} \lambda_i \left(\frac{\mathbf{r}_{ij}\mathbf{p}_{ij}}{\xi\hbar} - 1 \right)$$

$$\mathbf{r}_{ij} = |\mathbf{r}_i - \mathbf{r}_j|; \ \mathbf{p}_{ij} = |\mathbf{p}_i - \mathbf{p}_j|$$

Constrained Molecular Dynamics (CoMD)

S.Kimura and A.Bonasera, physics/0409008, Phys. Rev. A in press

Lagrange multiplier method for constraints

$$\mathcal{L} = \sum_{i} \frac{\mathbf{p}_i^2}{2m_i} - \sum_{i,j(\neq i)} U(\mathbf{r}_{ij}) + \sum_{i,j(\neq i)} \lambda_i \left(\frac{\mathbf{r}_{ij}\mathbf{p}_{ij}}{\xi\hbar} - 1 \right)$$

$$\mathbf{r}_{ij} = |\mathbf{r}_i - \mathbf{r}_j|; \ \mathbf{p}_{ij} = |\mathbf{p}_i - \mathbf{p}_j|$$

$$\xi = \begin{cases} 1 & \text{(for Heisenberg principle)} \\ 2\pi(3/4\pi)^{2/3} & \text{(for Pauli principle)} \end{cases}$$

Constrained Molecular Dynamics (CoMD)

S.Kimura and A.Bonasera, physics/0409008, Phys. Rev. A in press

Lagrange multiplier method for constraints

$$\mathcal{L} = \sum_i \frac{p_i^2}{2m_i} - \sum_{i,j(\neq i)} U(r_{ij}) + \sum_{i,j(\neq i)} \lambda_i \left(\frac{r_{ij} p_{ij}}{\xi \hbar} - 1 \right)$$

$$r_{ij} = |r_i - r_j|; \; p_{ij} = |p_i - p_j|$$

$$\xi = \begin{cases} 1 & \text{(for Heisenberg principle)} \\ 2\pi(3/4\pi)^{2/3} & \text{(for Pauli principle)} \end{cases}$$

Variational calculus leads Hamilton Equation with Constraint:

$$\frac{dr_i}{dt} = \frac{p_i}{m_i} + \frac{\lambda_i r_{ij}}{\xi \hbar} \frac{\partial p_{ij}}{\partial p_i}$$

$$\frac{dp_i}{dt} = -\nabla_r U(r_i) - \frac{\lambda_i p_{ij}}{\xi \hbar} \frac{\partial r_{ij}}{\partial r_i}$$

Convergence of Atomic G.S.

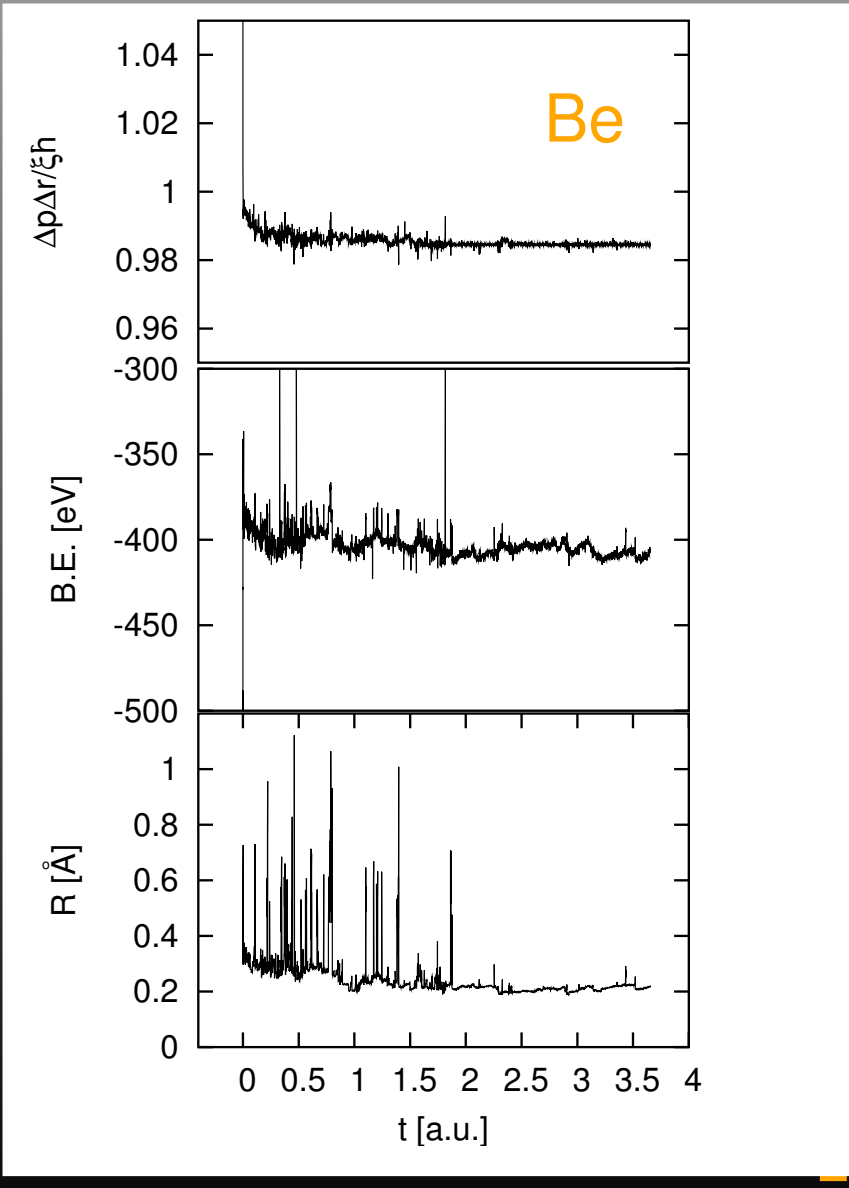
Constraint changes

Phase Space Occupation

$f(r,p,t) \leq 1$

Binding energies of Atoms(in eV)

	CoMD	exper.
H	−13.56	−13.61
He	−77.70	−78.88
Li	−203.78	−203.43
Be	−404.91	−399.03
F	−2644.4	−2713.45



Tunneling process

$$\frac{dr_i}{dt} = \frac{p_i}{m_i}; \qquad \frac{dp_i}{dt} = -\nabla_r U(r_i)$$

Collective coordinates and momenta

$$R^{coll} \equiv r_P - r_T; \qquad P^{coll} \equiv p_P - p_T; \qquad F_P^{coll} \equiv \dot{P}^{coll}$$

$$\frac{dr^{\Im}_{T(P)}}{d\tau} = \frac{p^{\Im}_{T(P)}}{m_{T(P)}}; \qquad \frac{dp^{\Im}_{T(P)}}{d\tau} = -\nabla_r U(r^{\Im}_{T(P)}) - 2F^{coll}_{T(P)}$$

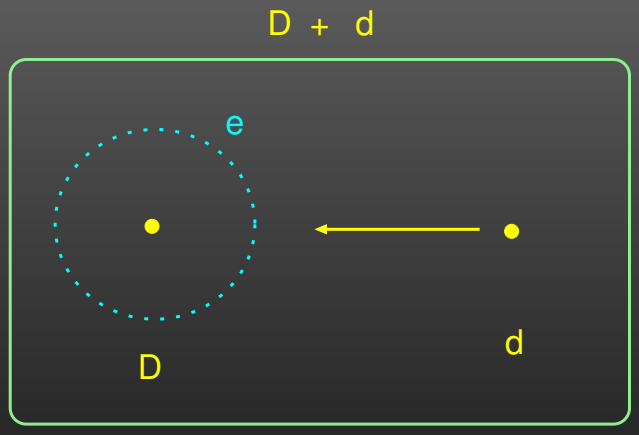
Tunneling penetrability: $\Pi(E) = \left(1 + \exp\left(2\mathcal{A}(E)/\hbar\right)\right)^{-1}$

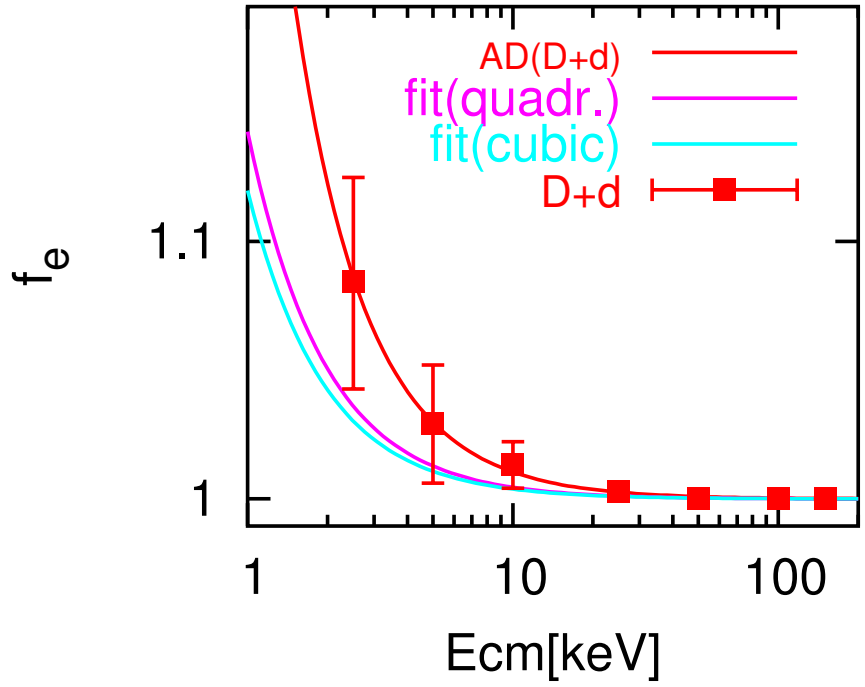
$$\mathcal{A}(E) = \int_{r_b}^{r_a} P^{coll}\, dR^{coll}$$

without electron $\Rightarrow \Pi_0(E)$

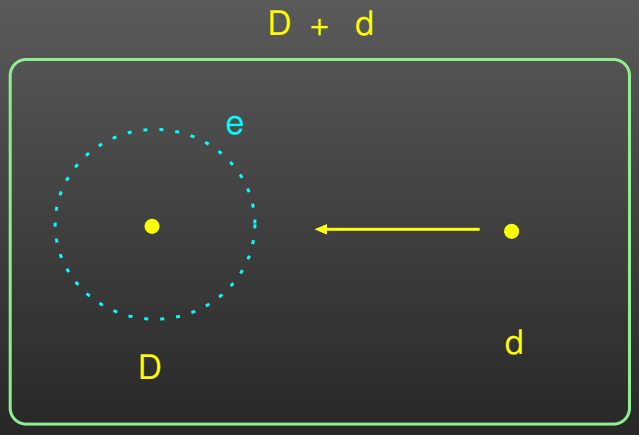
Enhancement factor: $f_e = \Pi(E)/\Pi_0(E)$

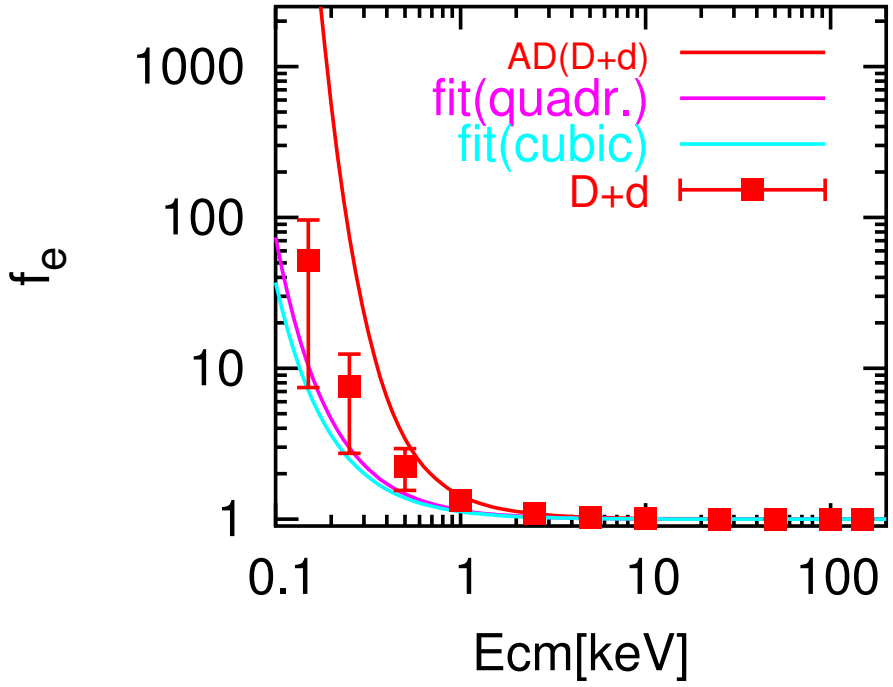
Enhancement factor
and
Variance $\Sigma = \sqrt{\bar{f}_e^2 - (\bar{f}_e)^2}$



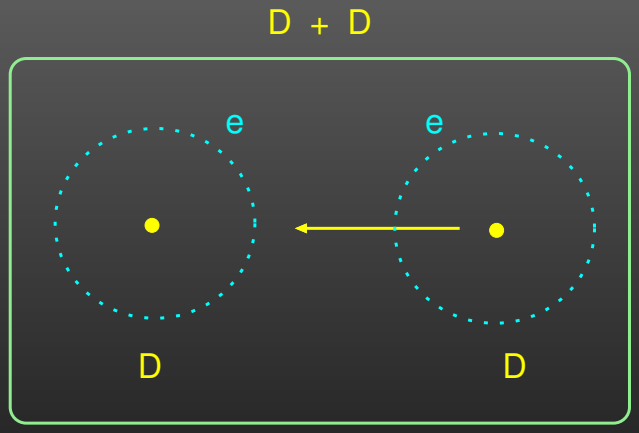


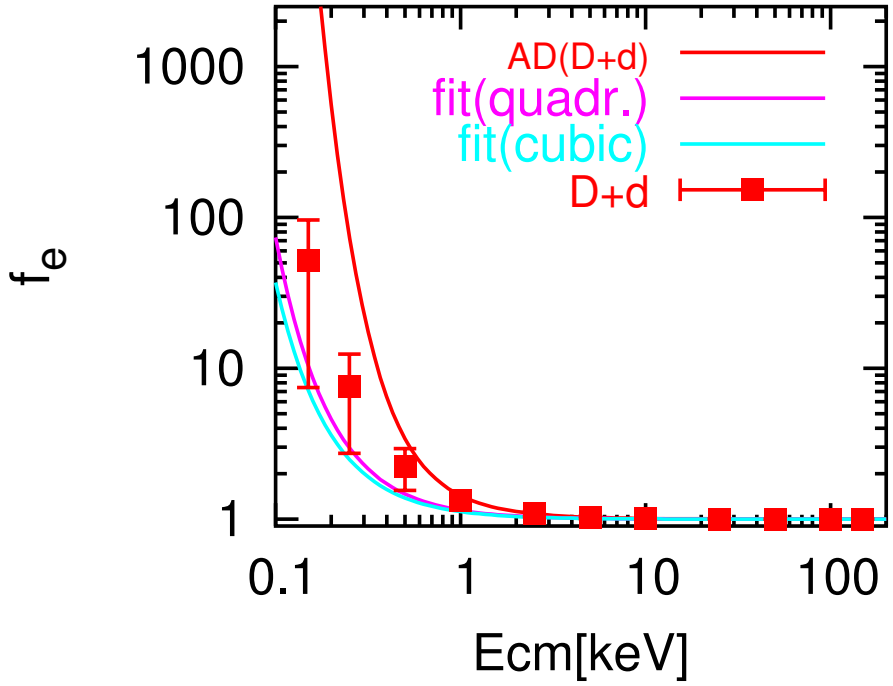
Enhancement factor
and
Variance $\Sigma = \sqrt{\bar{f}_e^2 - (\bar{f}_e)^2}$



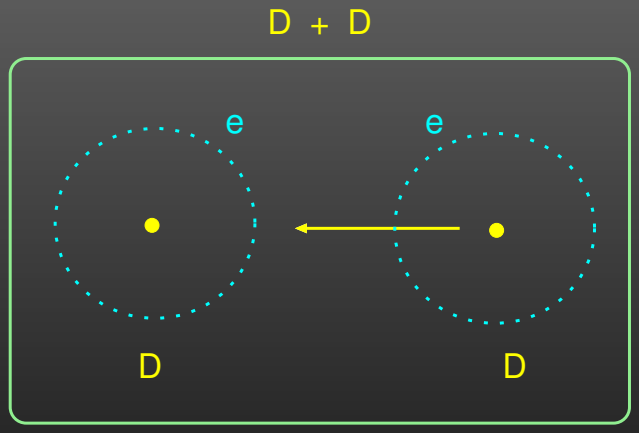


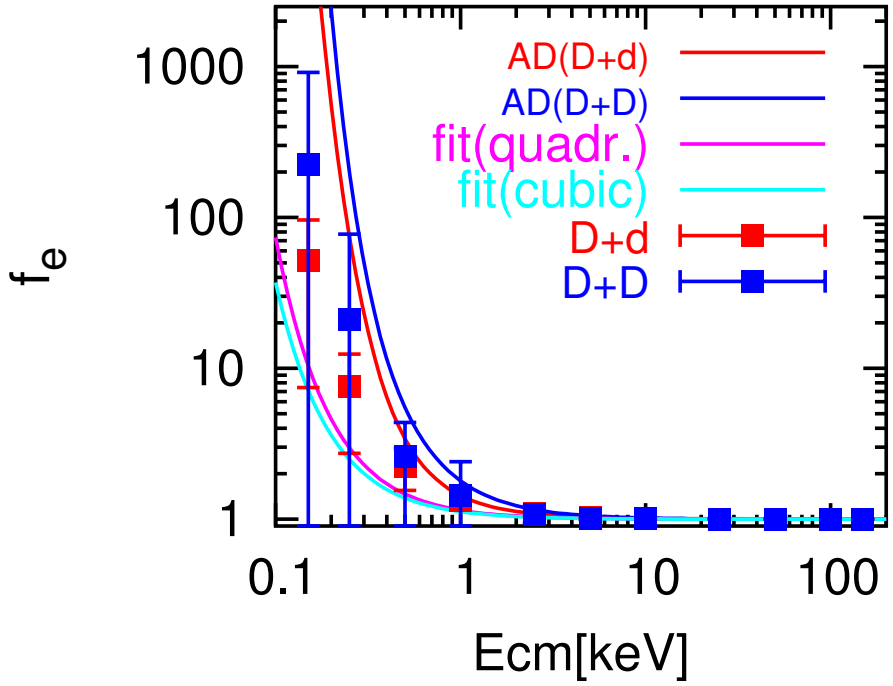
Enhancement factor
and
Variance $\Sigma = \sqrt{\bar{f}_e^2 - (\bar{f}_e)^2}$





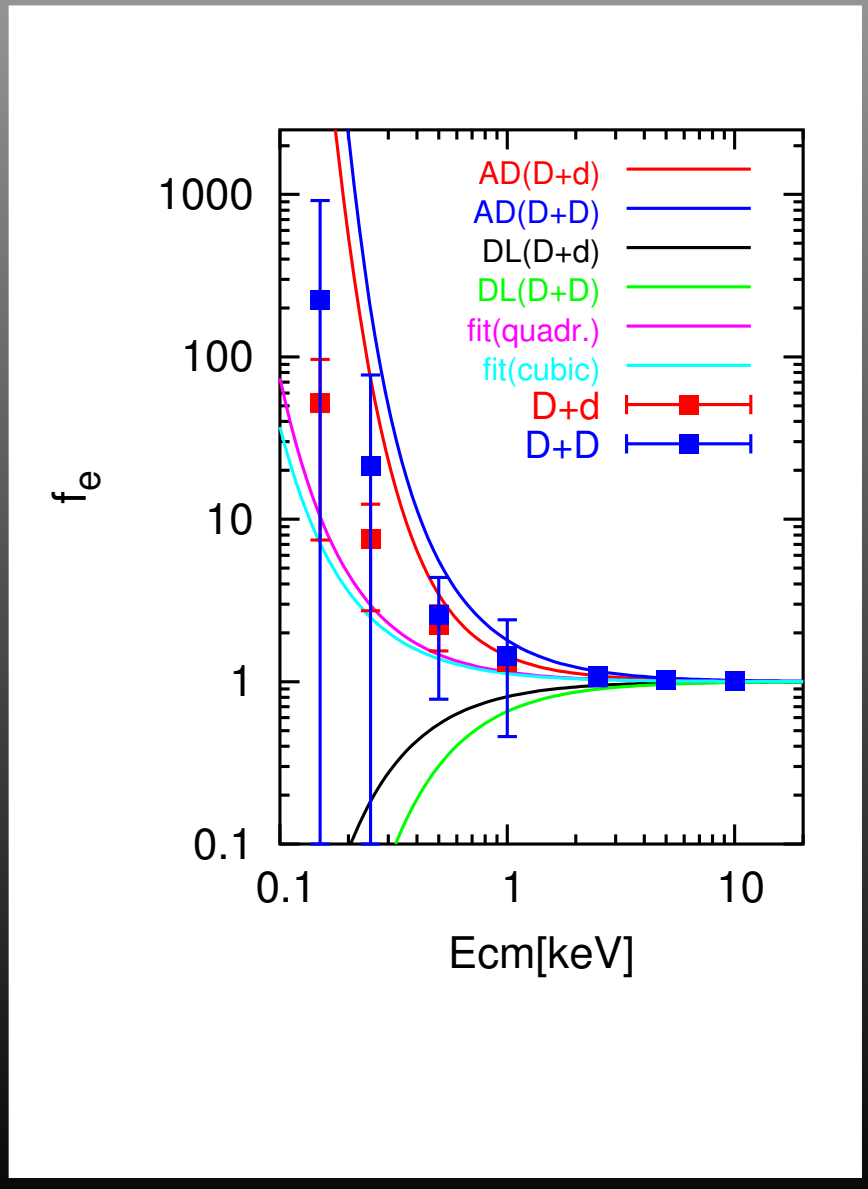
Enhancement factor
and
Variance $\Sigma = \sqrt{\bar{f}_e^2 - (\bar{f}_e)^2}$



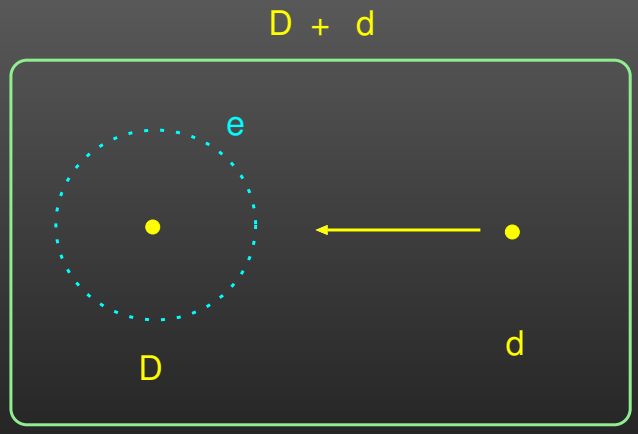


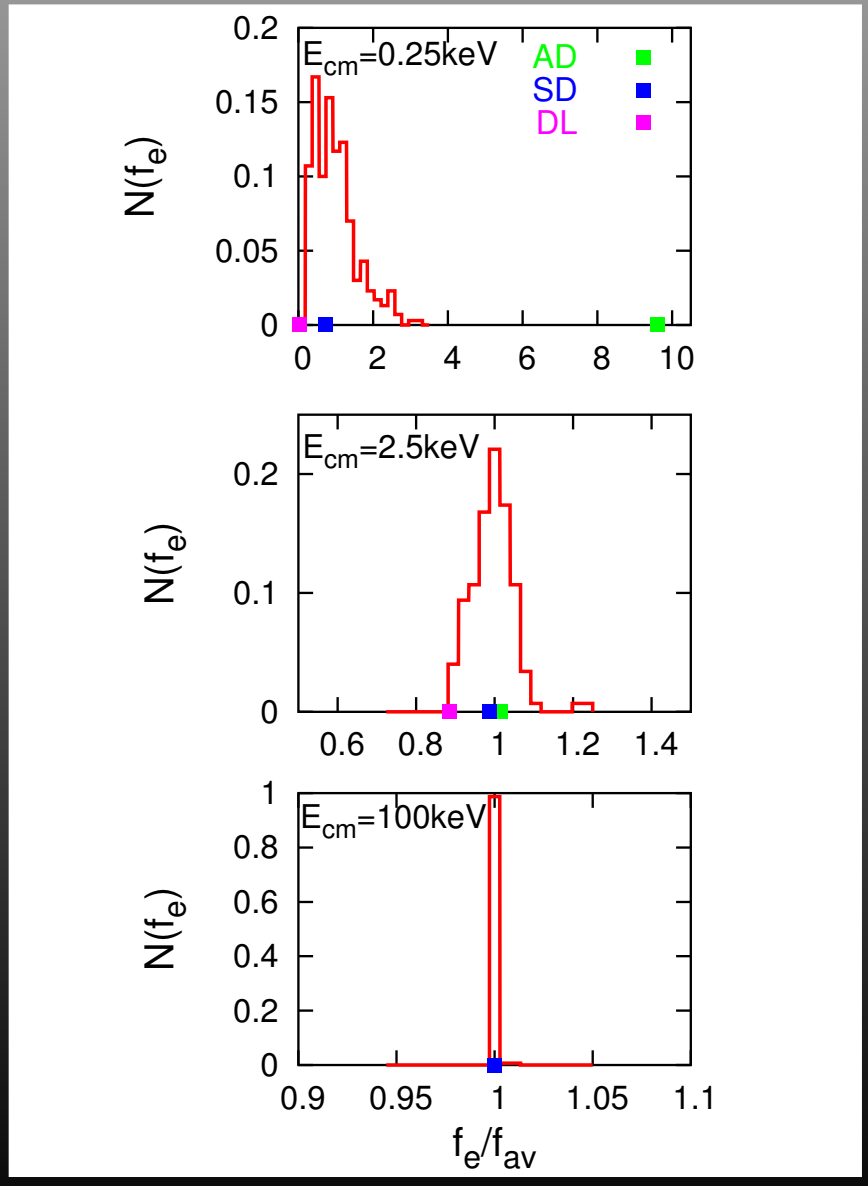
Dissipative Limit

Bound electron emission



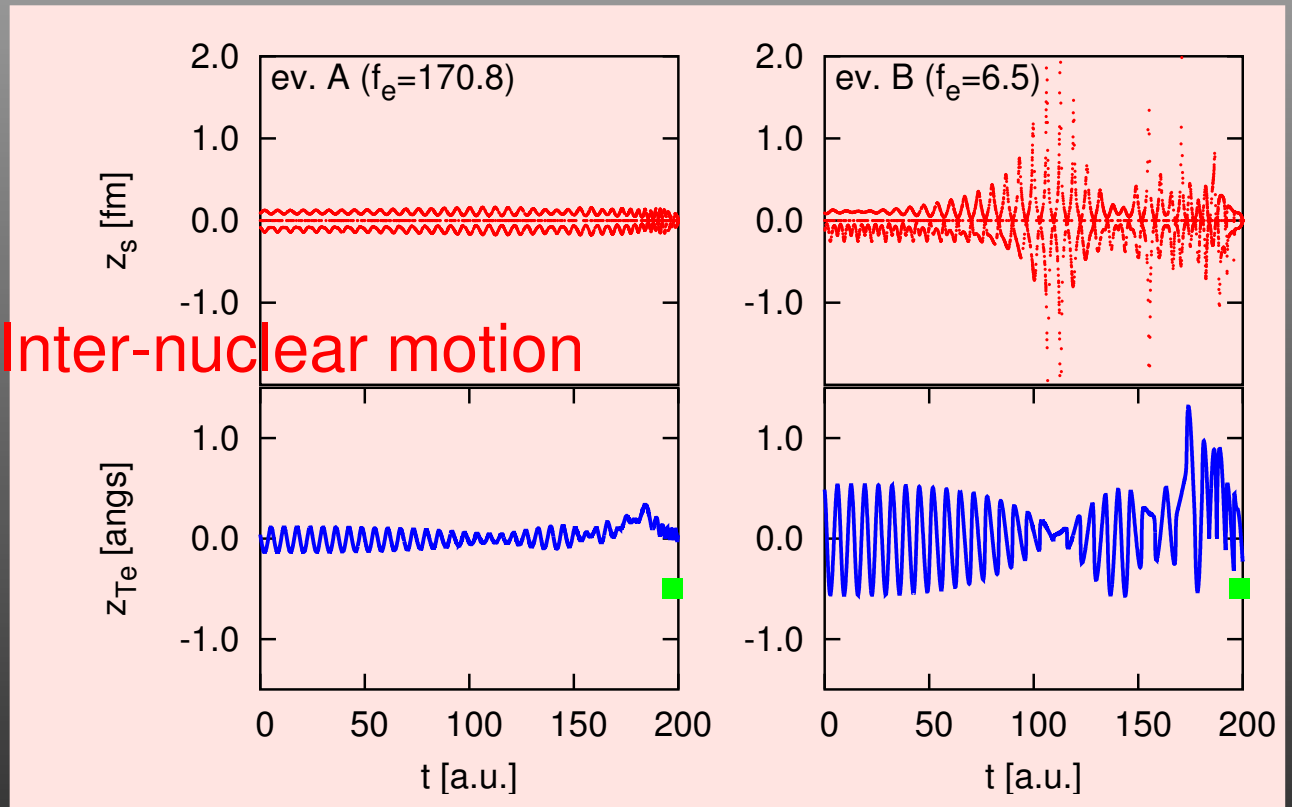
Change of Distribution





Electronic Motion

S.Kimura, and A.Bonasera
Phys.Rev.Lett.**93**,
262502(2004)

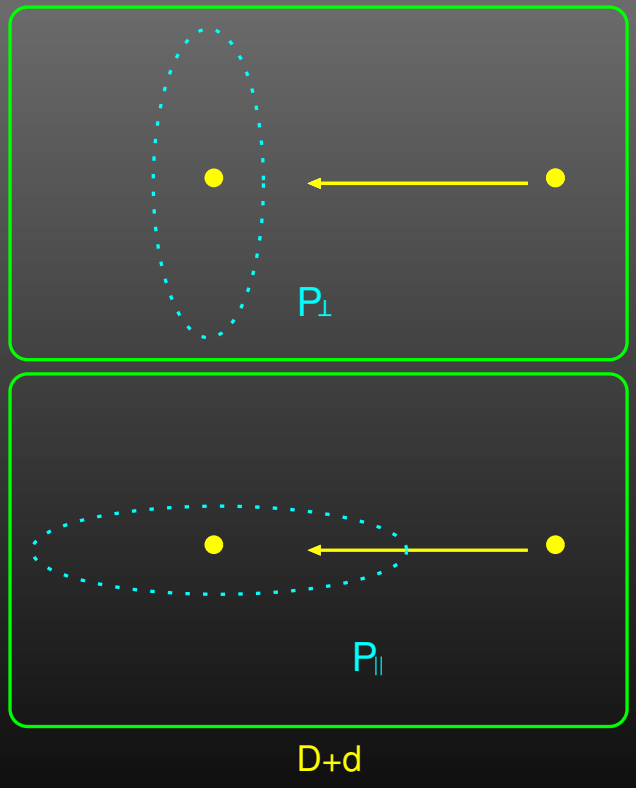


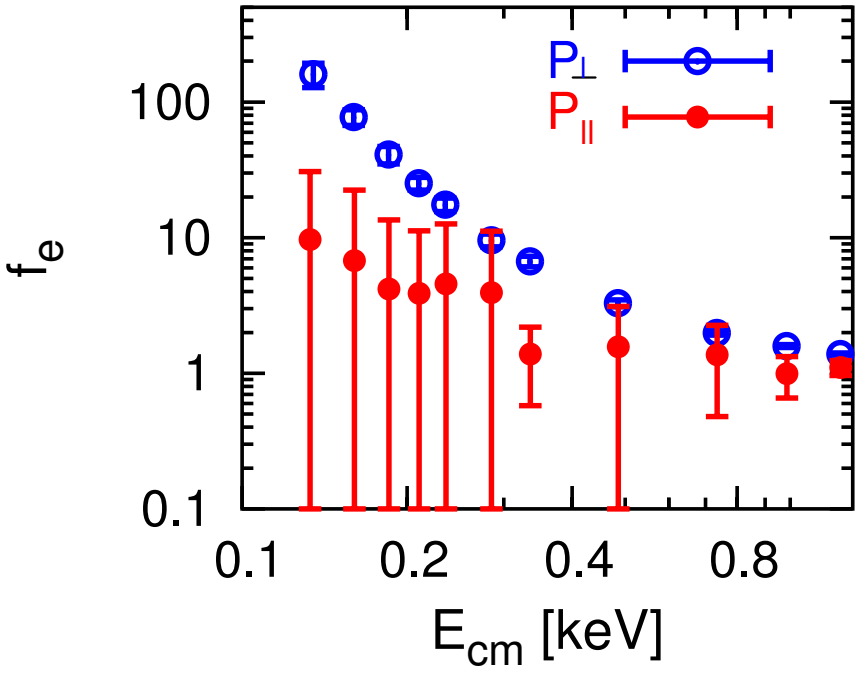
Sensitive Initial Phase

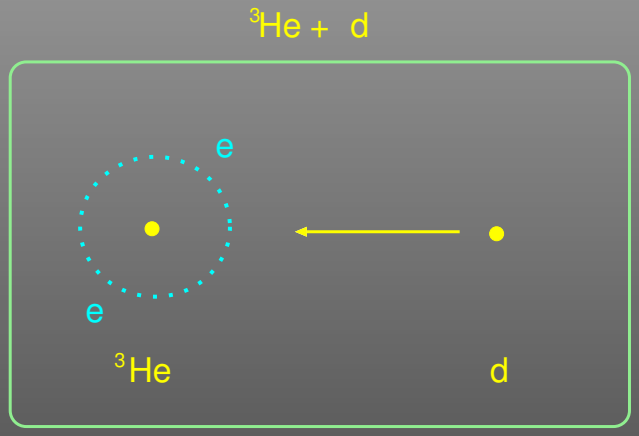
Space Configuration Dependence $\Rightarrow$ Chaos

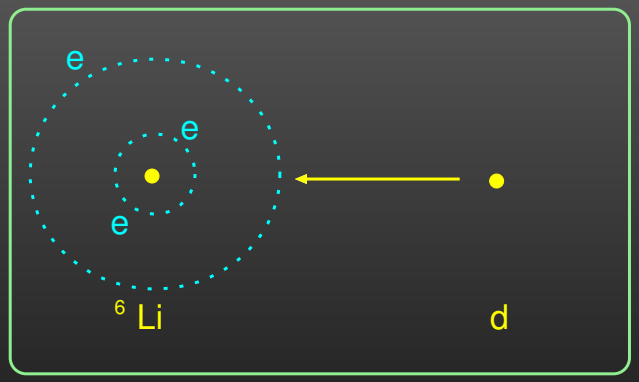
Polarized Target

Enhancement factor with Polarized target

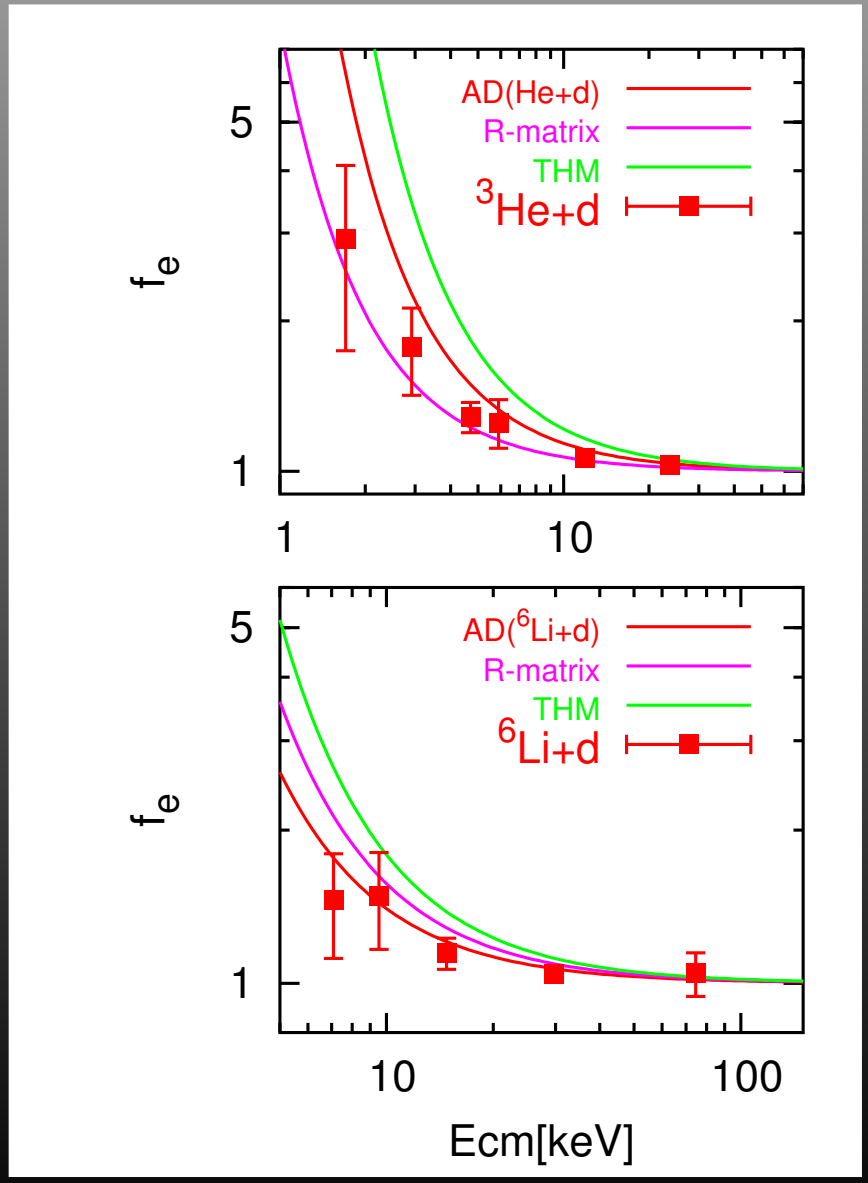


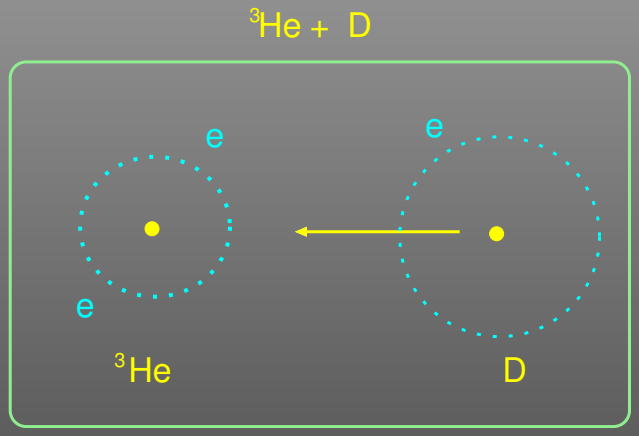


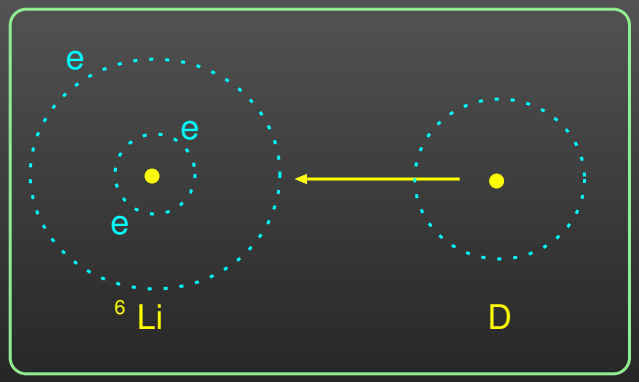




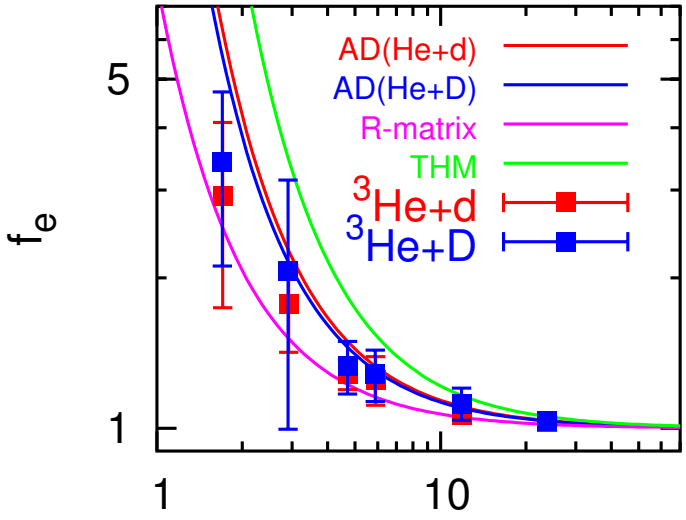
S.Kimura, and A. Bonasera
Nucl.Phys.A in press
nucl-th/0504005

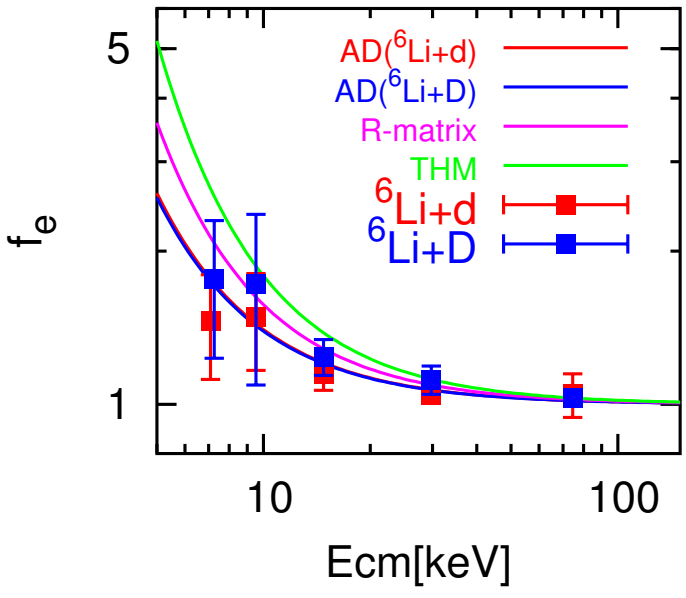






S.Kimura, and A. Bonasera
Nucl.Phys.A in press
nucl-th/0504005





Summary

Influence of Chaos on the Fusion Enhancement by Electron Screening

- Determination of the fusion enhancement factor for the reactions D+d,^{3}He+d, ^{6}Li+d, D+D, ^{3}He+D, ^{6}Li+D
- Both the averaged f_e and variance increases as the incident energy becomes lower, however $\bar{f}_e < f_e^{(AD)}$
- In Low Energy region, Sensitive dependence on initial configurations: evidence of Chaos
- Chaotic motion of bound electrons affects f_e
- Dissipative Limit: Bound electron emission
- With polarized target, perpendicular to the beam
  $\Rightarrow$ Large enhancement of the reaction rate