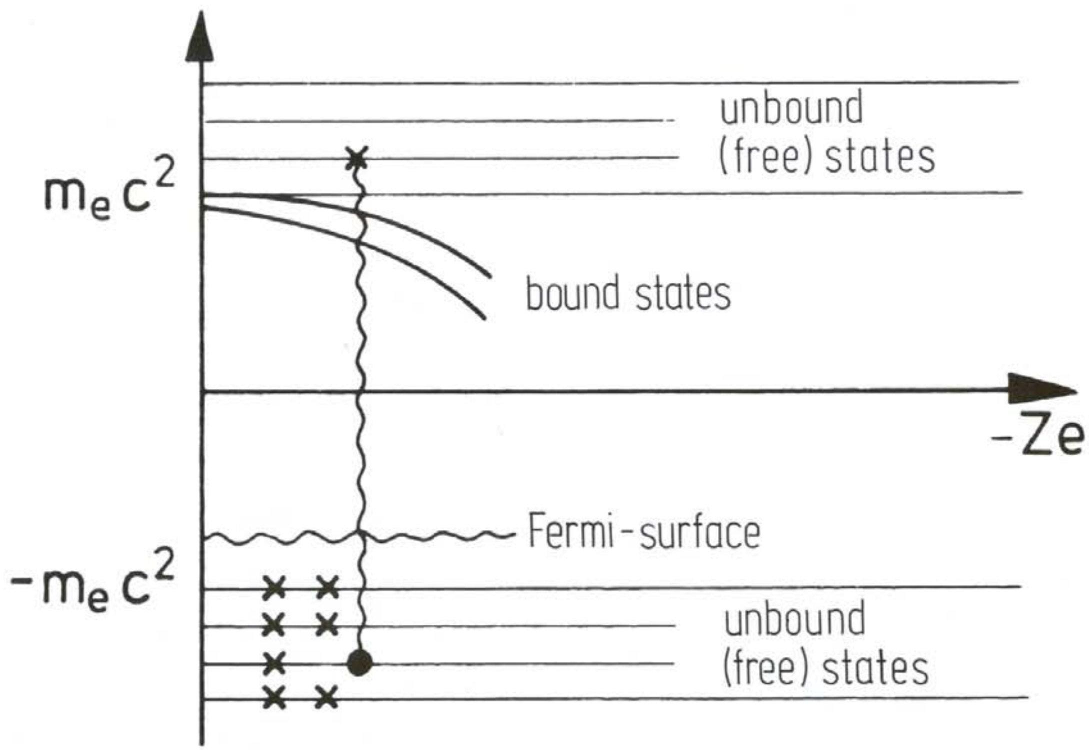
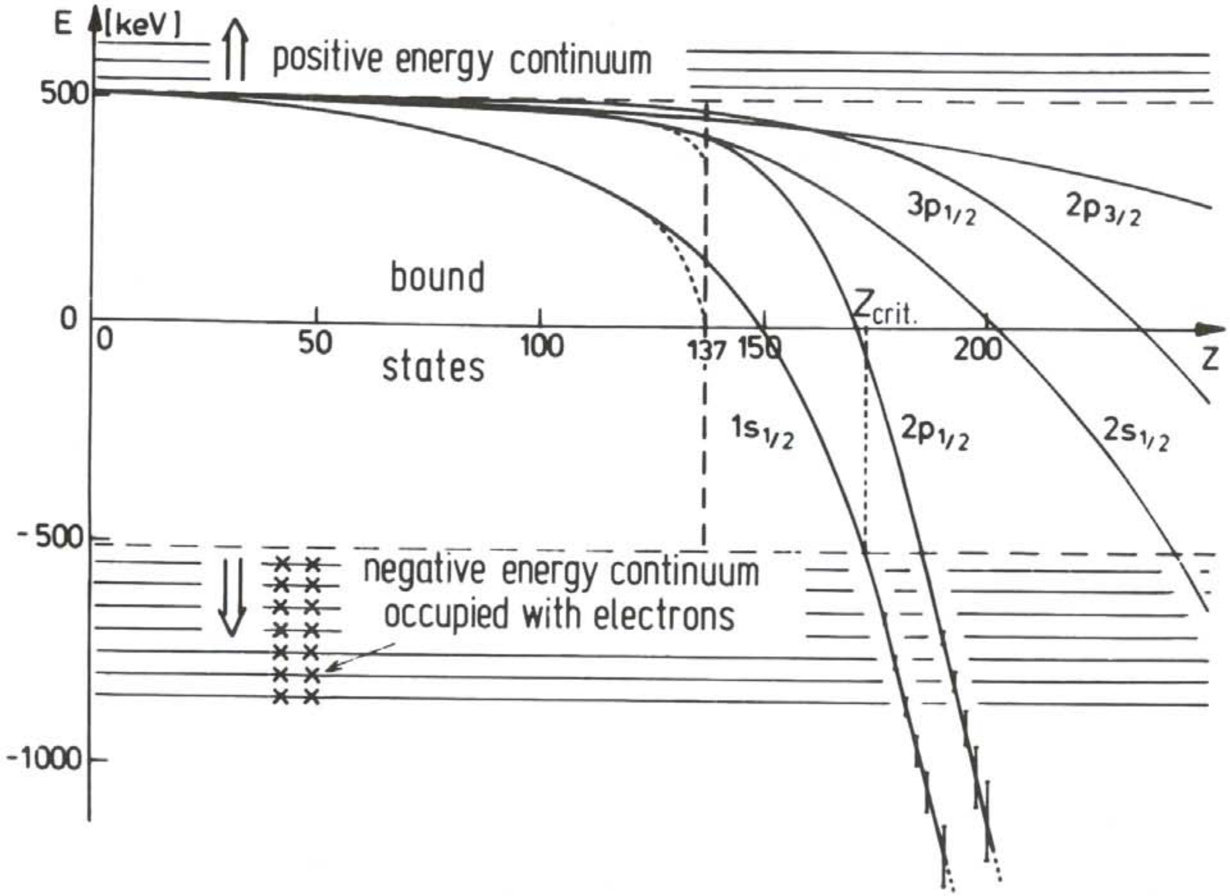
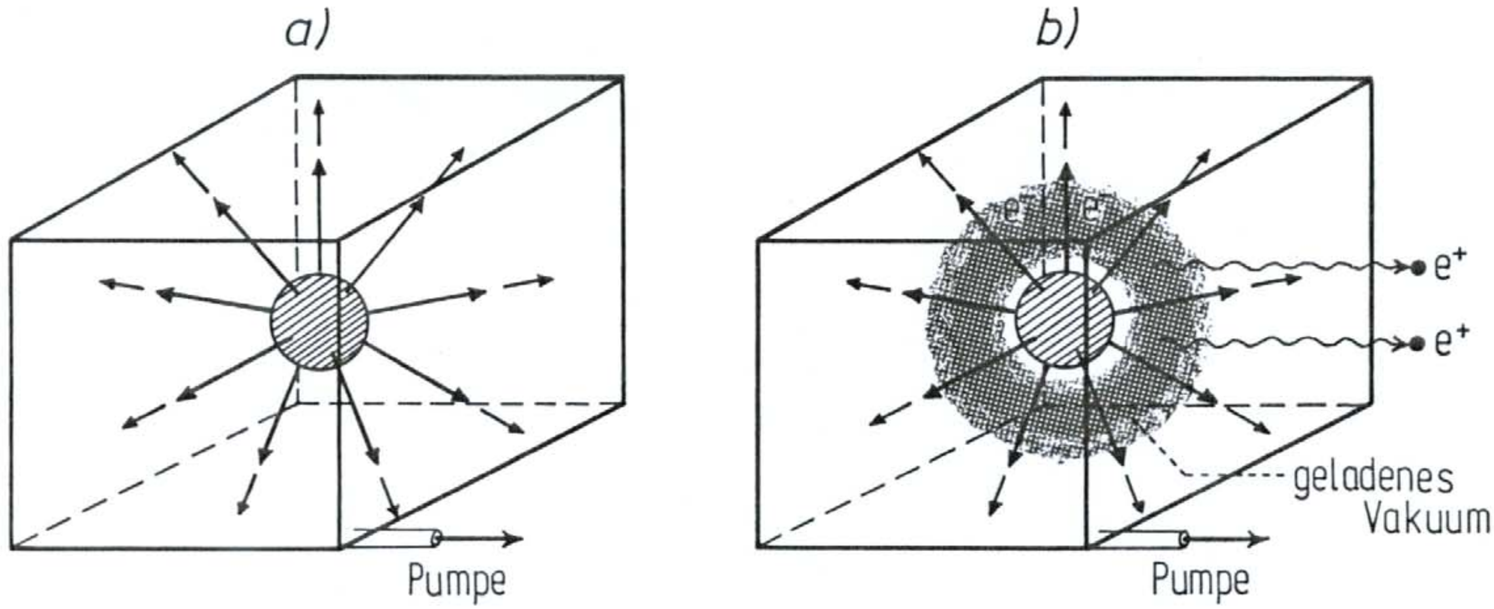
Vacuum Structure in QED



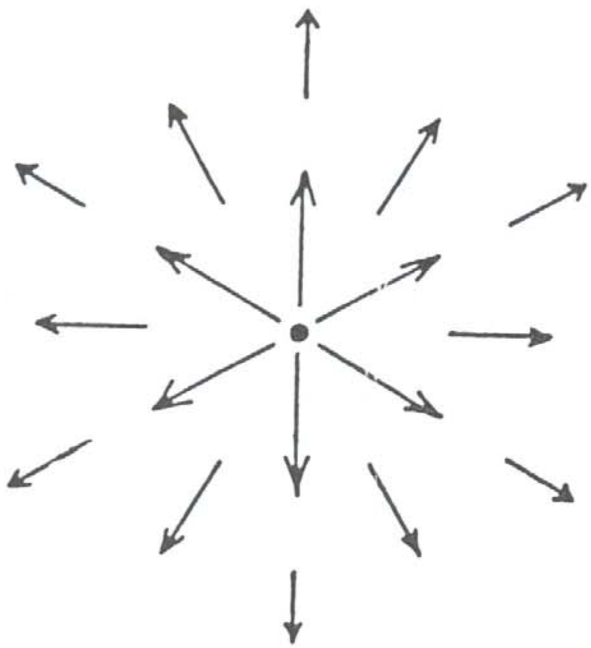
$$E = \pm\sqrt{c^2 p^2 + \left(m_e c^2\right)^2}$$



E [keV]
positive energy continuum
500
bound
states
0
0
50
100
137
150
200
Z
$Z_{crit.}$
$3p_{1/2}$
$2p_{3/2}$
$1s_{1/2}$
$2p_{1/2}$
$2s_{1/2}$
-500
negative energy continuum
occupied with electrons
-1000



UFfm TP82-055



Ein isotropes Kraftfeld ist in jeder Richtung gleich beschaffen

QED

Statevector:

$$\hat{\psi}(\vec{x},0) = \sum_{p} \hat{b}_p \psi_p(\vec{x}) + \sum_{n} \hat{a}_n^{+} \psi_n(x)$$

current:

$$\hat{j}_\mu = 1/2 \, [\, \hat{\bar{\psi}}, \gamma_\mu \; \hat{\psi} \,]_{-}$$

density:

$$\hat{\rho} = 1/2 \, [\, \hat{\psi}^{+}(\vec{x},0), \; \hat{\psi}(\vec{x},0) \,]_{-}$$

vacuum polarization charge:

$$< 0 \mid \hat{\rho} \mid 0 > = \rho_{vac\,pol} =$$

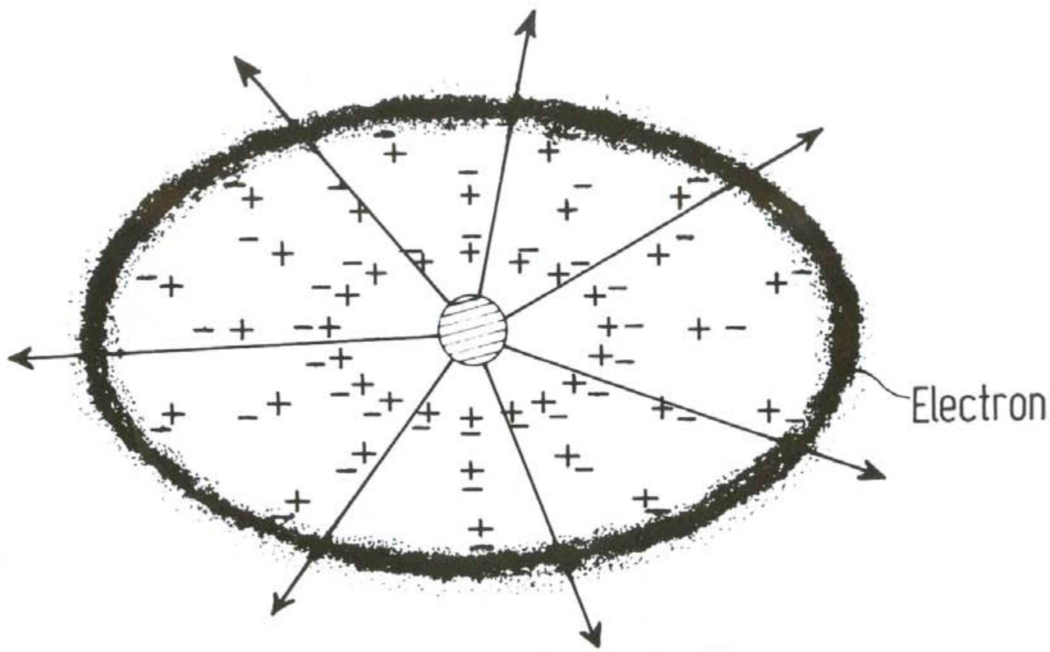
$$= 1/2 \, e \left(\sum_{n} \psi_n^{+} \psi_n - \sum_{p} \psi_p^{+} \psi_p \right)$$

displacement charge:

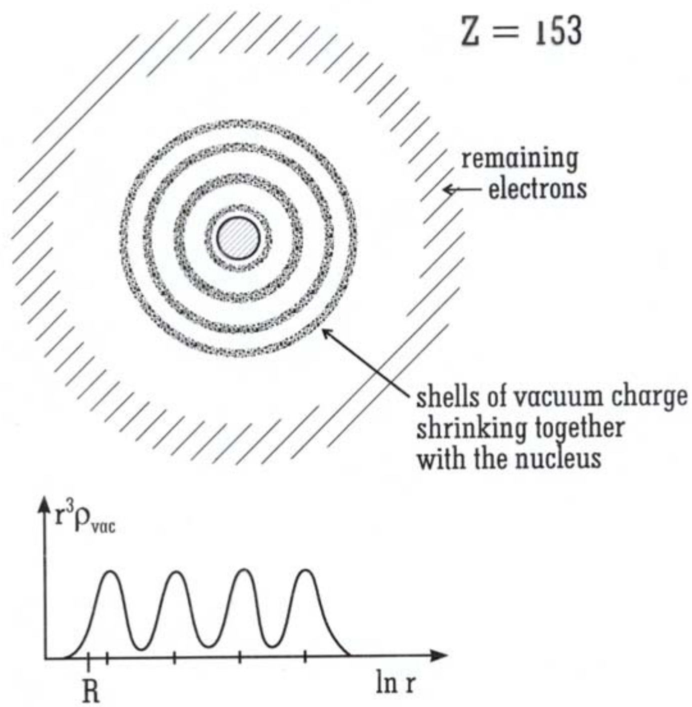
$$\int_{V} \rho_{vac\,pol}(\vec{x}) \, d^3x = 0$$

Charged Vacuum

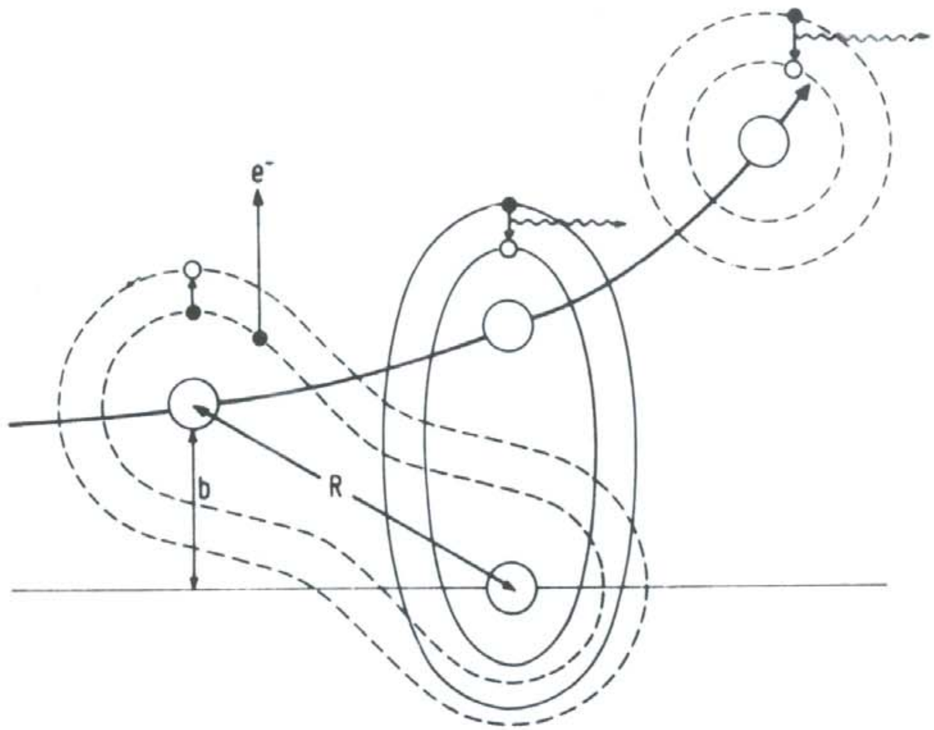
$$\int \langle \text{charged vac.} \mid \hat{\rho} \mid \text{charged vac.} \rangle \, d^3x =$$
$$= 2e, 4e, ...$$



Electron feels vacuum polarisation
⟹ part of the so called Lamb shift



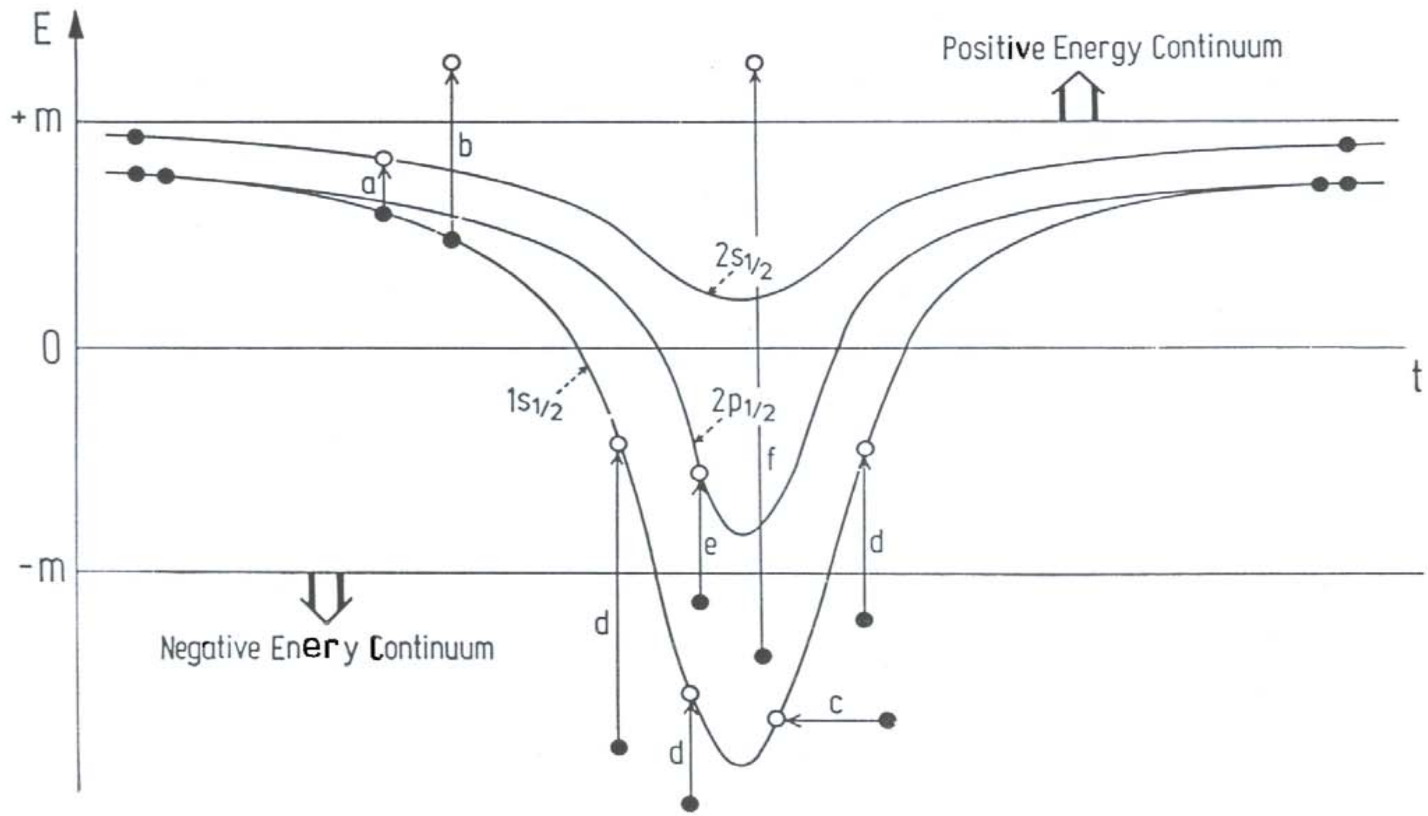
Point nucleus limit
(B. Müller, P. Gärtner
U. Heinz)



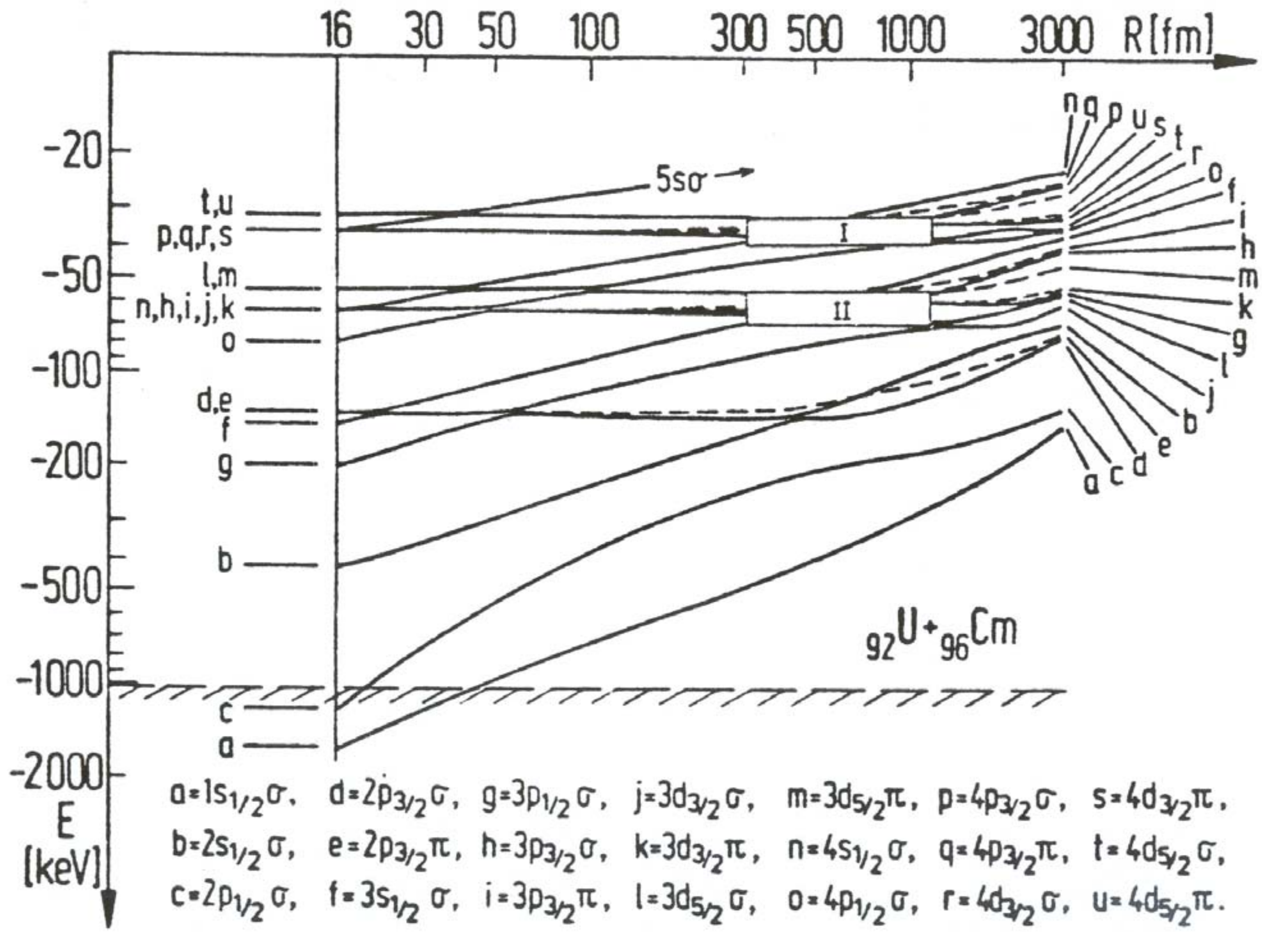
Superheavy quasi molecule

Superheavy quasi atom

J. Reinhardt, G. Soff, U. Müller



E
+m
0
-m
t
Positive Energy Continuum
Negative Enery Continuum
$1s_{1/2}$
$2s_{1/2}$
$2p_{1/2}$
a
b
c
d
d
d
d
e
f



B. Müller, W. Betz, …

Semiclassical trajectory

$$i\hbar\frac{\partial}{\partial t}\phi_i(R(t)) = \hat{H}_{\mathrm{TCD}}(R(t))\,\phi_i(R(t))$$

$$\phi_i(R(t)) = \sum_j a_{ij}(t)\varphi_j(R(t))\,e^{i\chi_j}$$

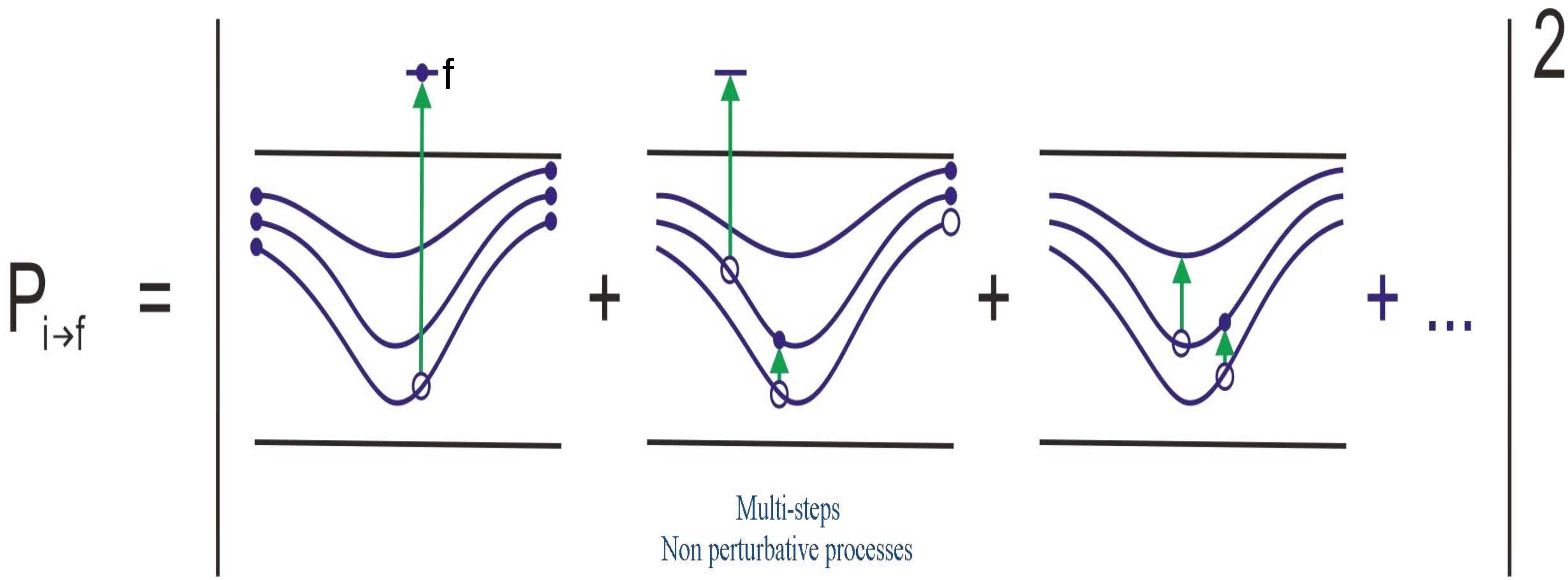
$$\dot{a}_{ij}(t) = -\sum_{k\neq j} a_{ik}\langle\varphi_i|\frac{\partial}{\partial t}\varphi_k\rangle\,e^{i(\chi_k-\chi_i)}$$

Number of particles:

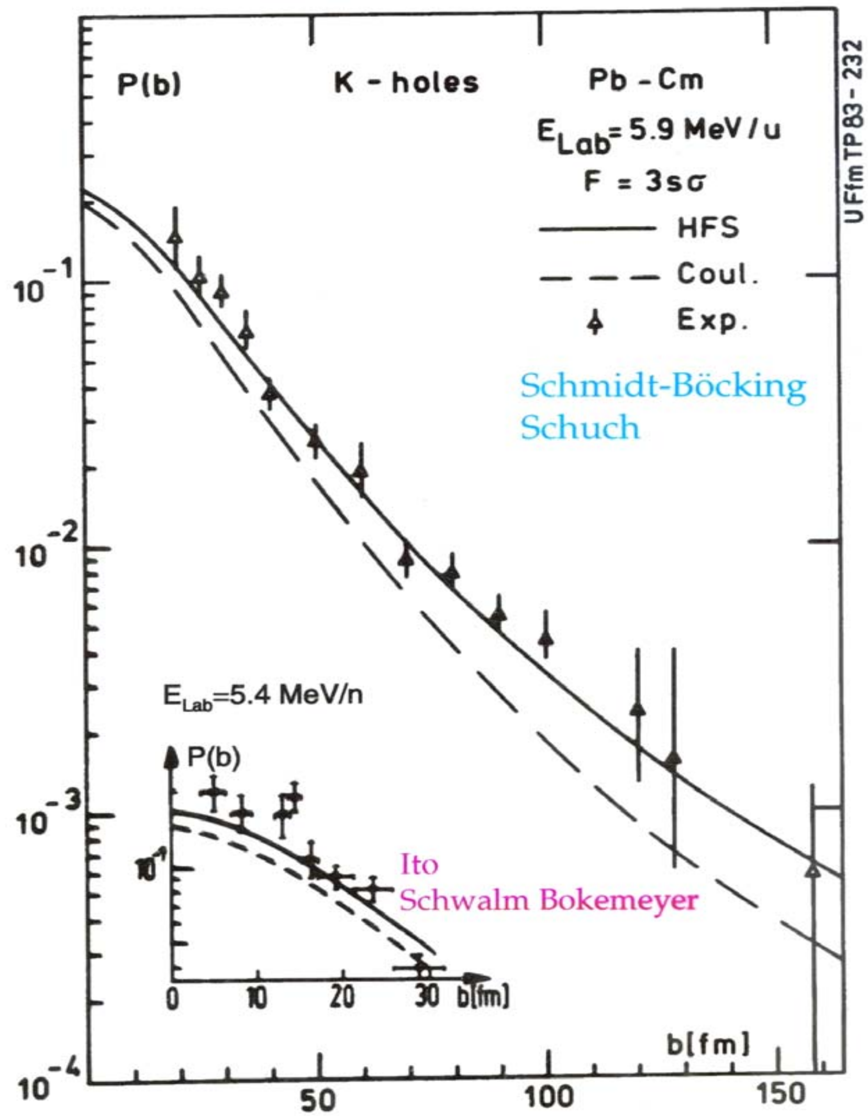
$$N_p = 2\sum_{k<F}|a_{kp}(\infty)|^2 \qquad (p>F)$$

Number of holes:

$$N_p = 2\sum_{k>F}|a_{kp}(\infty)|^2 \qquad (p<F)$$


$P_{i\to f}$ =
f
+
+
+ ...
2
Multi-steps
Non perturbative processes

Experiments: Schmidt-Böcking, Schuch
Theory: de Reus, U. Müller, J. Reinhardt



Meyerhof - Demkov - contribution
must be taken care of!

Quasimolecular Spectroscopy using K-vacancy rate $P_{1s\sigma}(b)$

1st order perturbation theory

$$P_{1s\sigma}(b) = 2 \int_m^\infty |a_{1s,E}|^2$$

$$a_{1s,E} \simeq \int_{-\infty}^{+\infty} dt \, \langle \varphi_E | \frac{\partial}{\partial R} | \varphi_{1s} \rangle \, \dot{R} \; e^{-i \int^t d\tau (E - E_{1s\sigma}(\tau))}$$

Scaling formula (approximate solution of the integral)

$$P_{1s\sigma}^{\text{pert}}(b) \simeq D(Z) \, N(Z, b, v) \;\; e^{\frac{2\tau_0}{\hbar} E_{1s}(R_0)}$$

where R_0: distance of closest approach

τ_0: characteristic collision time $\tau_0 = \frac{1}{v}(b + a(\pi - \arctan \frac{b}{a}))$

Inverting the function leads to $E_{1s}(R)$

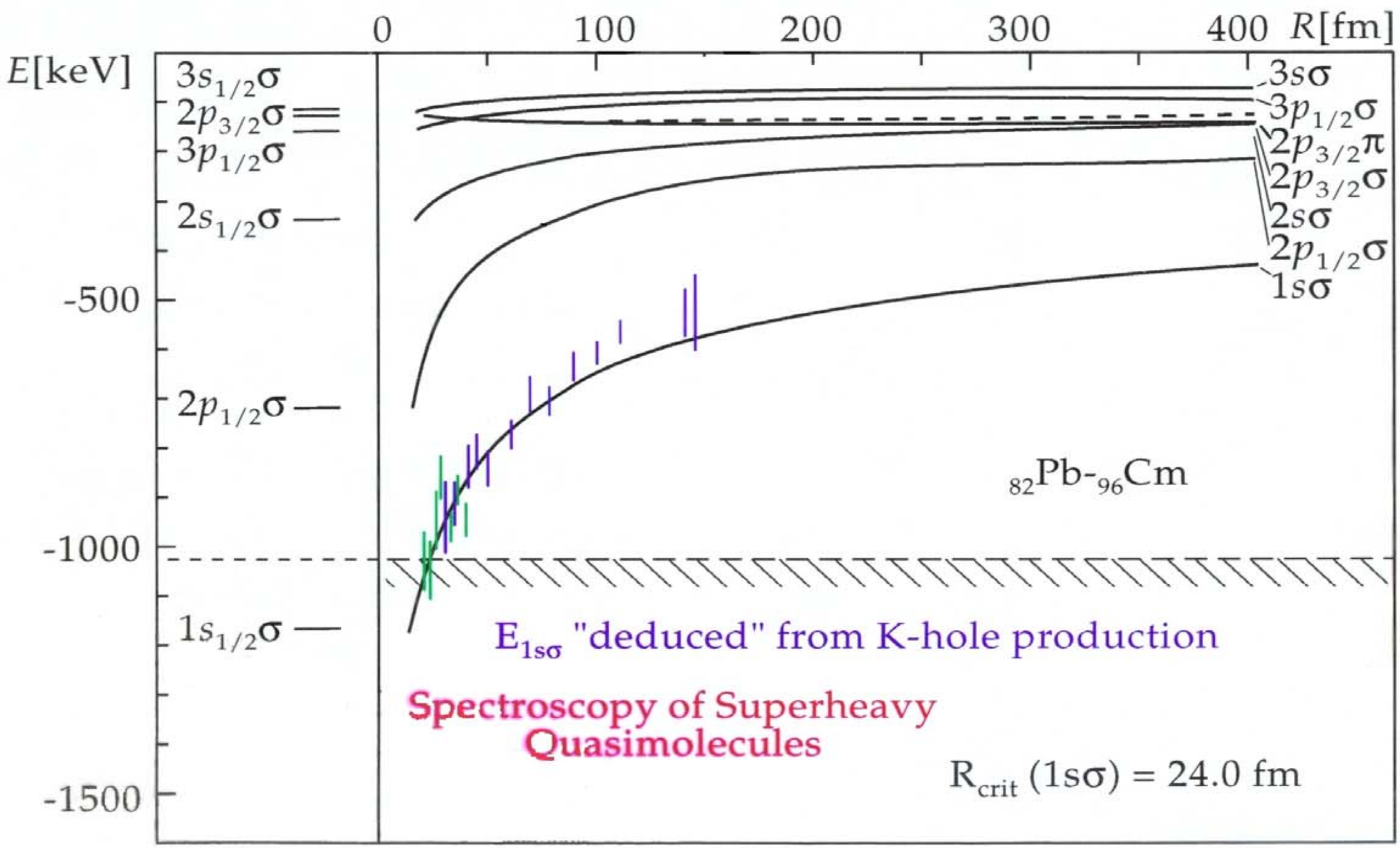
Problem: Perturbation theory not really valid (multi-step processes)

From Coupled channel calculations one finds:

$P_{1s\sigma}^{\text{cc}} / P_{1s\sigma}^{\text{pert}} \simeq 5$ (no analytical expression available)

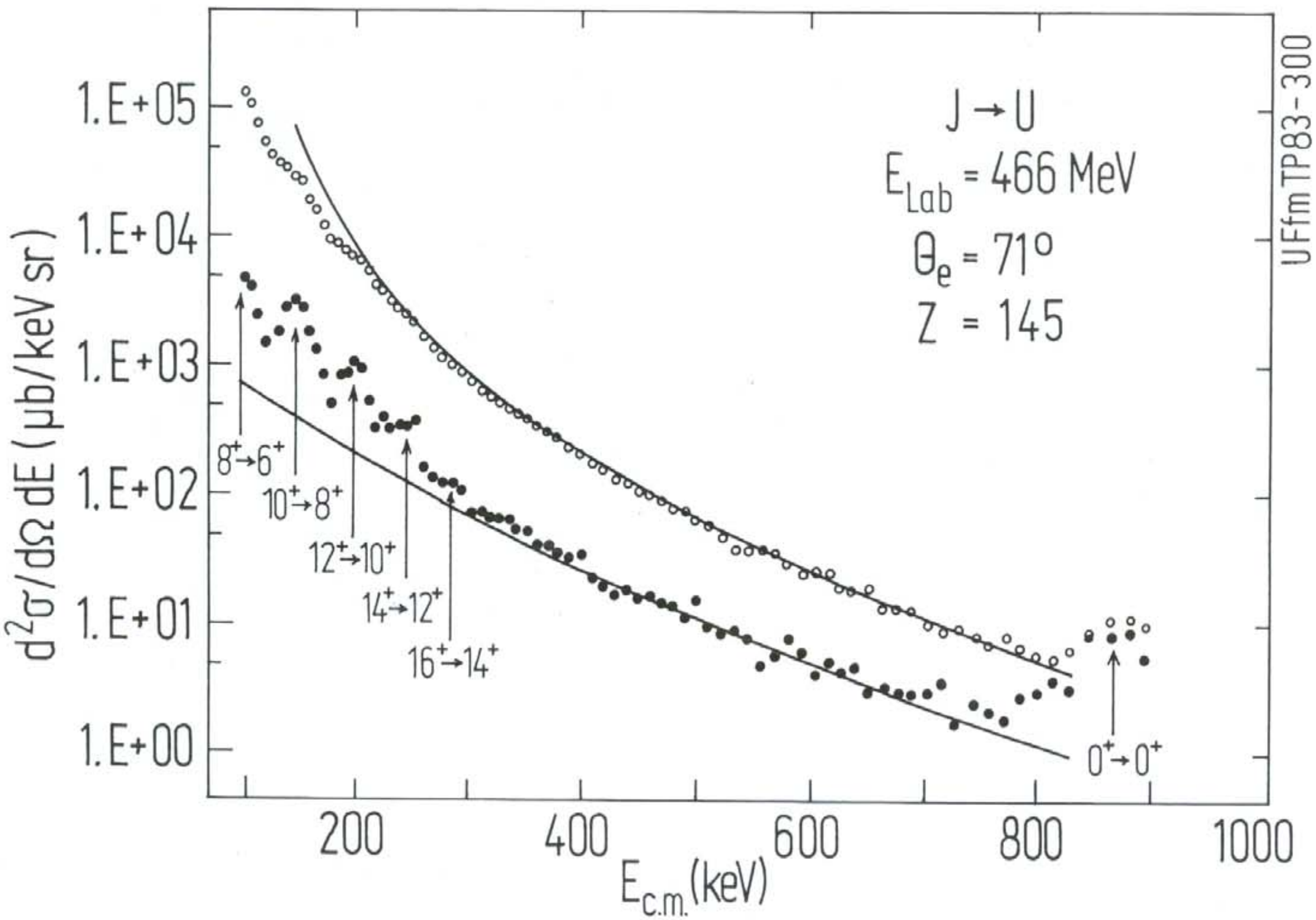
Additional problem in (near-)symmetric systems:

Contamination by vacancy sharing of $P_{1s\sigma}$ and $P_{2p_{1/2}\sigma}$

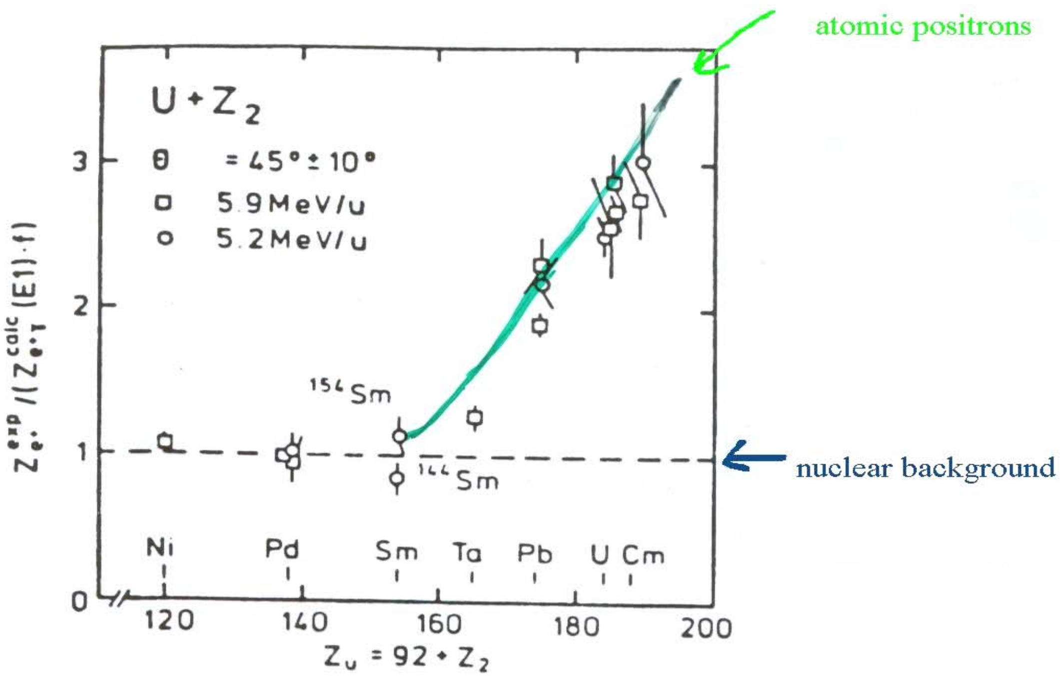


0
100
200
300
400
R[fm]
E[keV]
3s1/2σ
2p3/2σ
3p1/2σ
2s1/2σ
-500
2p1/2σ
-1000
1s1/2σ
-1500
3sσ
3p1/2σ
2p3/2π
2p3/2σ
2sσ
2p1/2σ
1sσ
82Pb-96Cm
E1sσ "deduced" from K-hole production
Spectroscopy of Superheavy Quasimolecules
Rcrit (1sσ) = 24.0 fm

Delta-electron spectrum

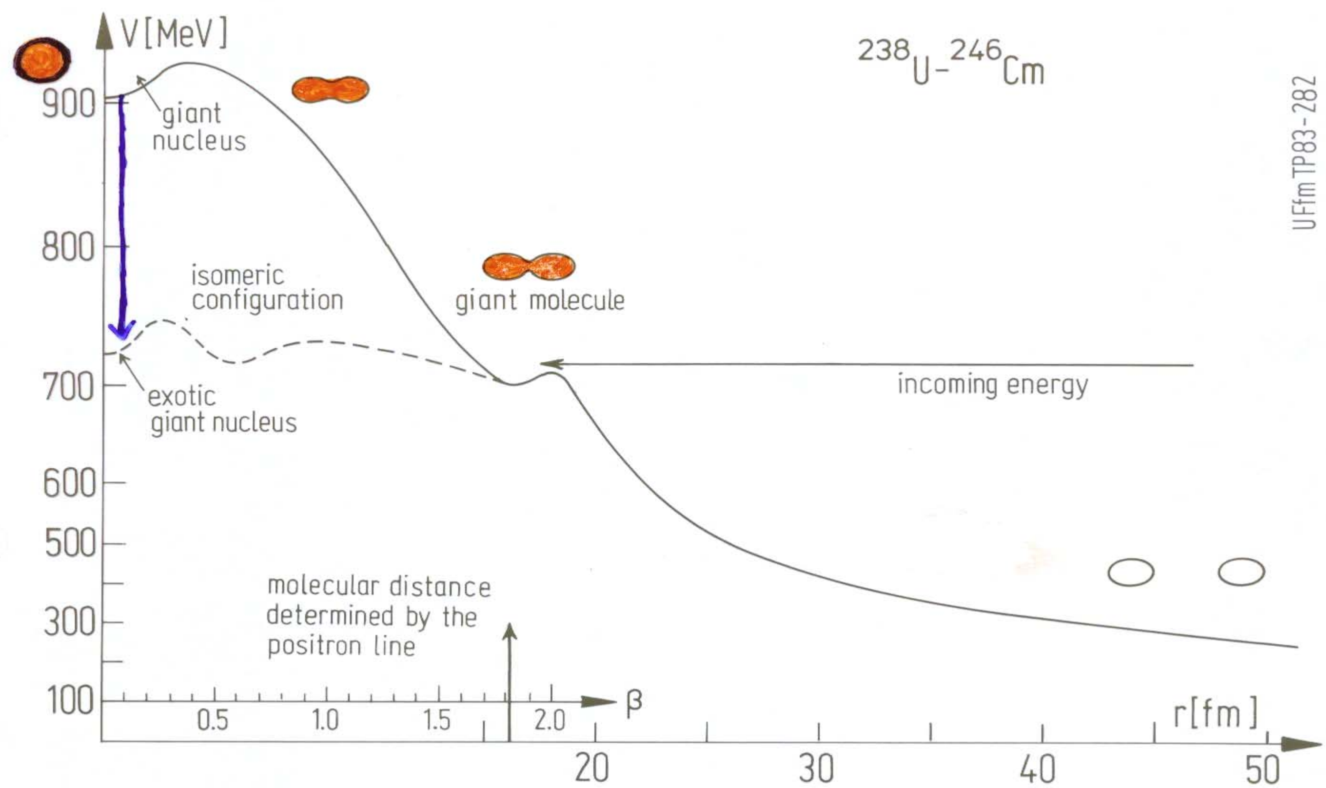


Exp.: Ramayya, König et. al.
Calcul.: de Reus, U. Müller

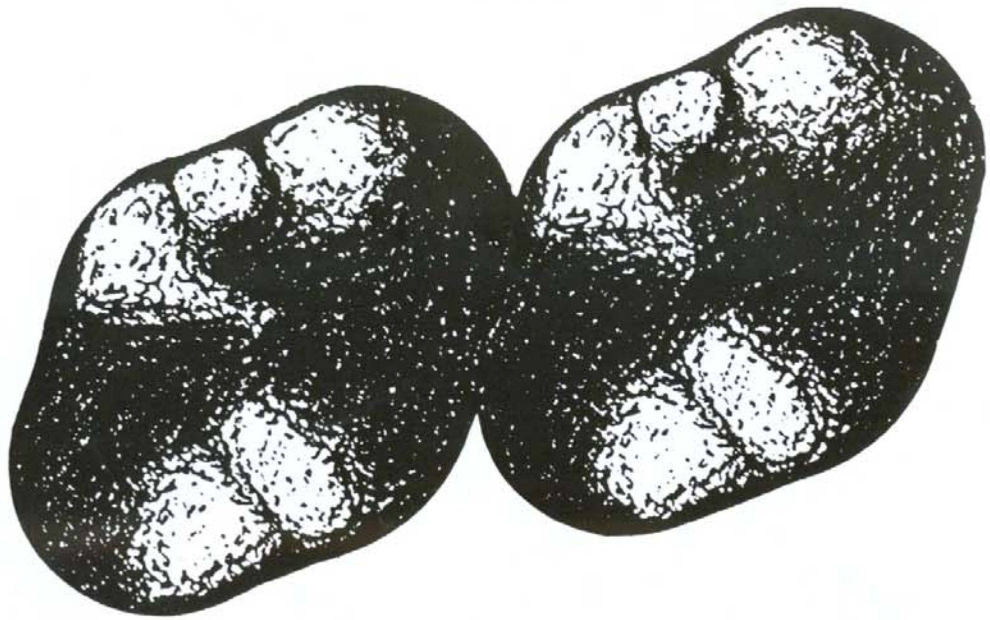


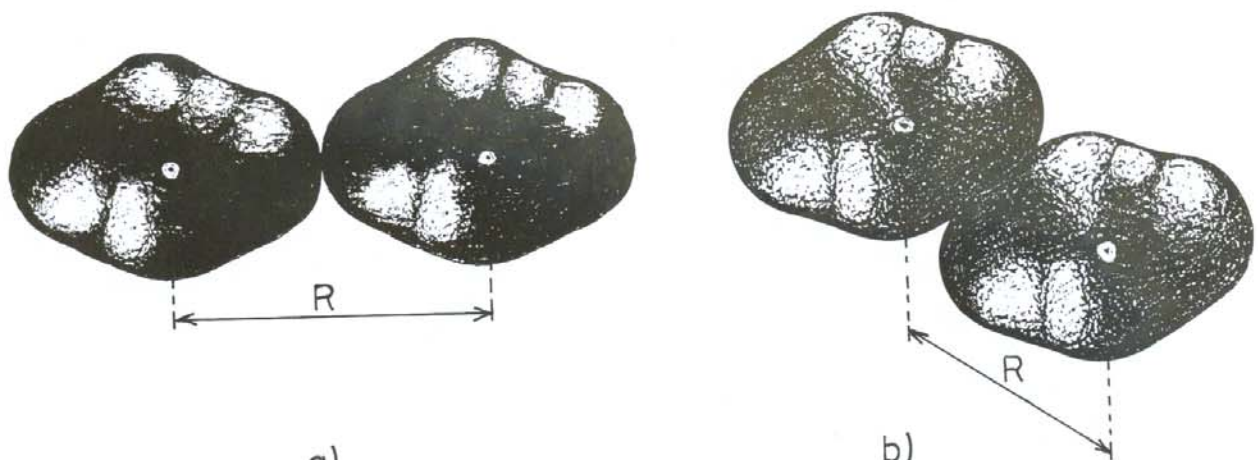
U + Z2
θ = 45° ± 10°
5.9MeV/u
5.2MeV/u
154Sm
144Sm
Ni
Pd
Sm
Ta
Pb
U
Cm
0
1
2
3
120
140
160
180
200
Zu = 92 + Z2
atomic positrons
nuclear background

Backe et al.

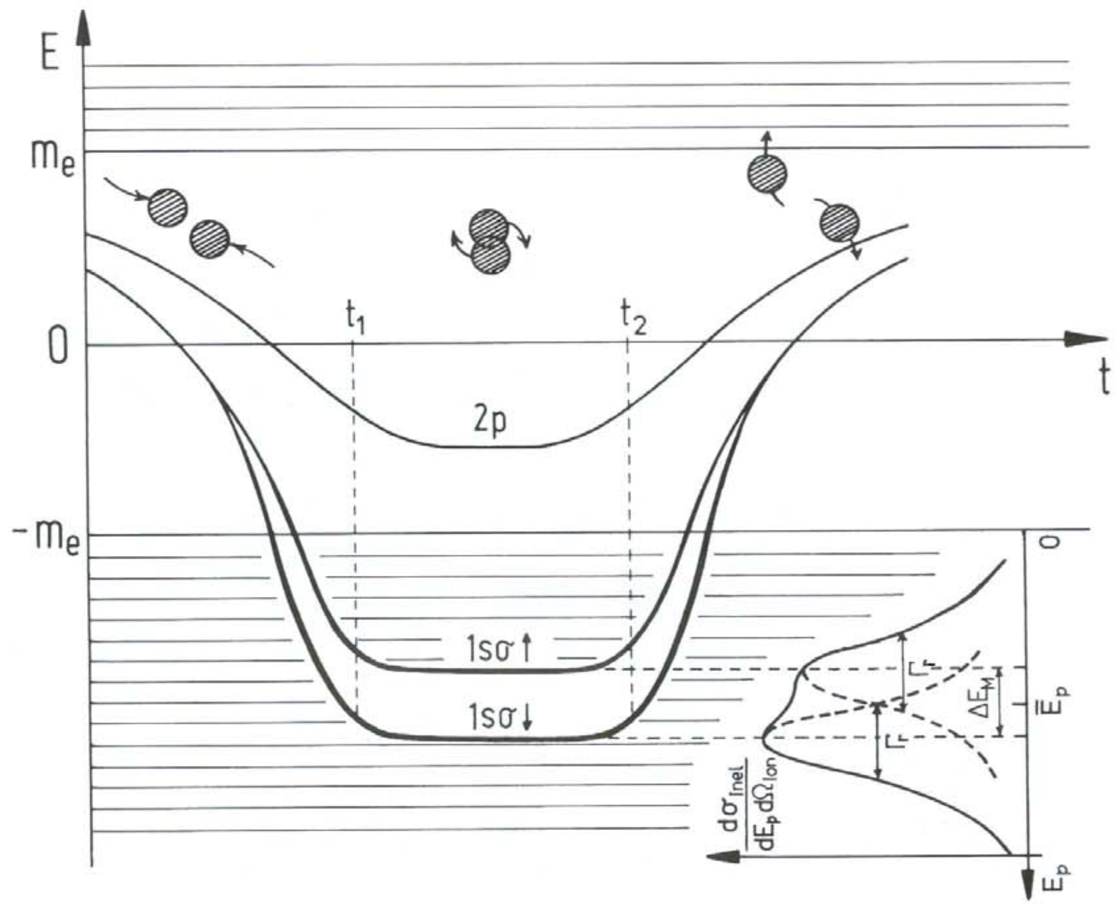


Isomeric Configurations of the "giant" nuclear complex

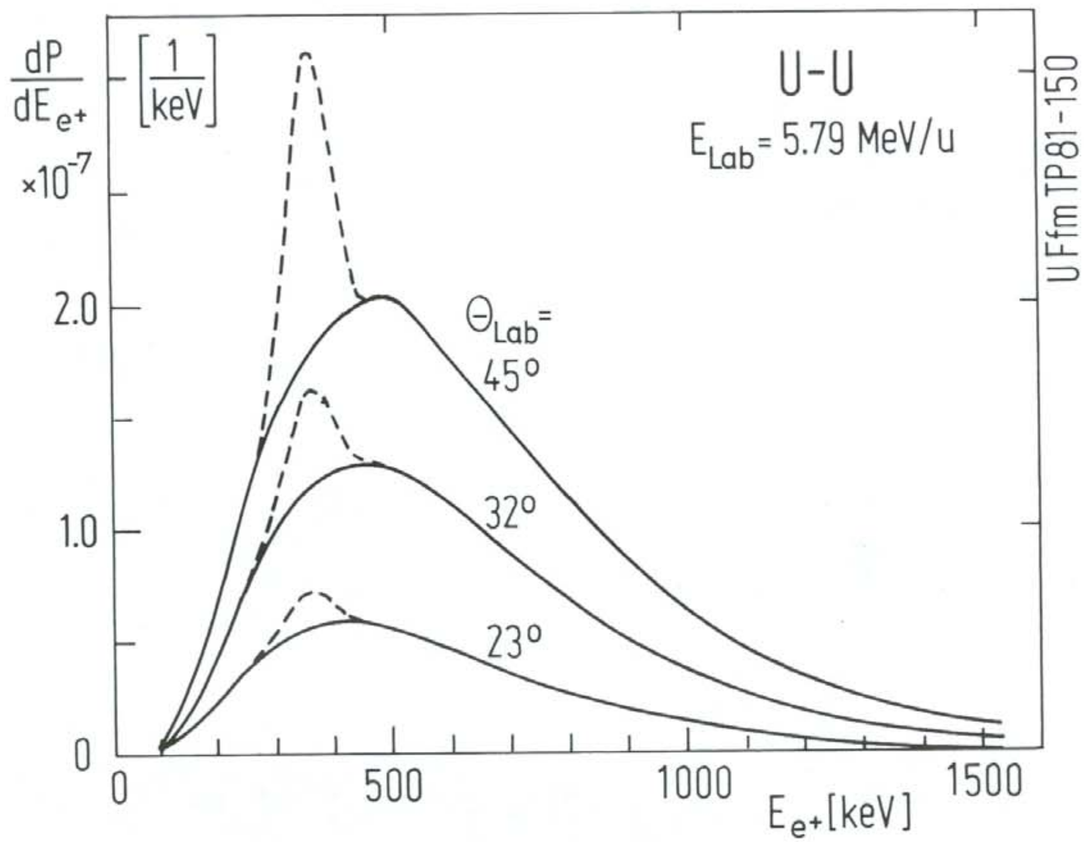




a) b)



E
m_e
0
t
t_1
t_2
2p
$-m_e$
$1s\sigma\uparrow$
$1s\sigma\downarrow$
Γ_r
ΔE_M
$\bar{E}_p$
$\frac{d\sigma_{inel}}{dE_p d\Omega_{ion}}$
E_p

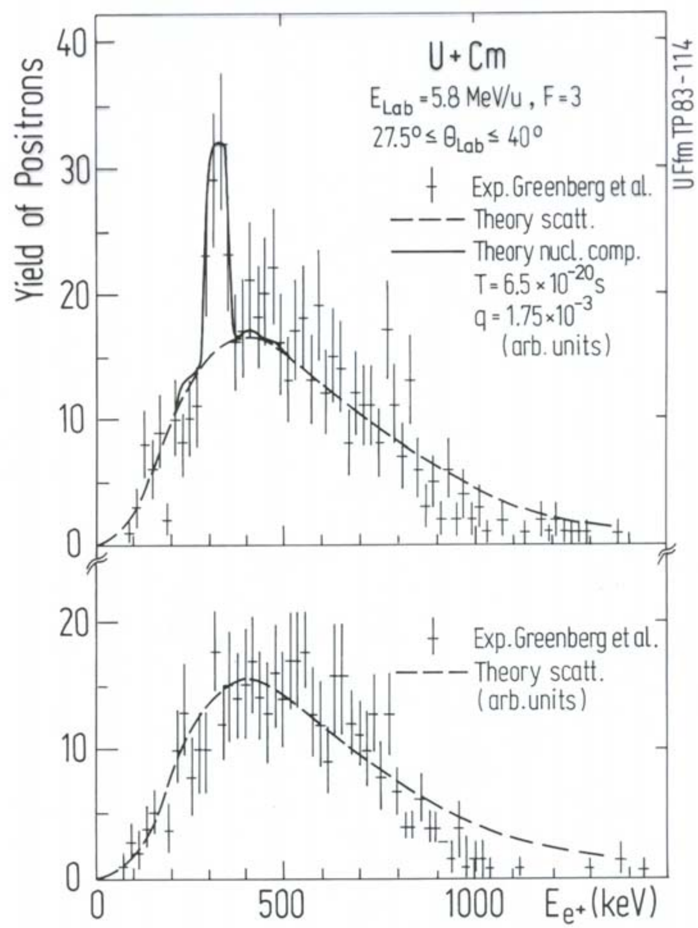


$\frac{dP}{dE_{e+}}$ $\left[\frac{1}{keV}\right]$
$\times 10^{-7}$
U-U
E_{Lab} = 5.79 MeV/u
UFfm TP81-150
2.0
1.0
0
Θ_{Lab}=
45°
32°
23°
0
500
1000
1500
E_{e+}[keV]

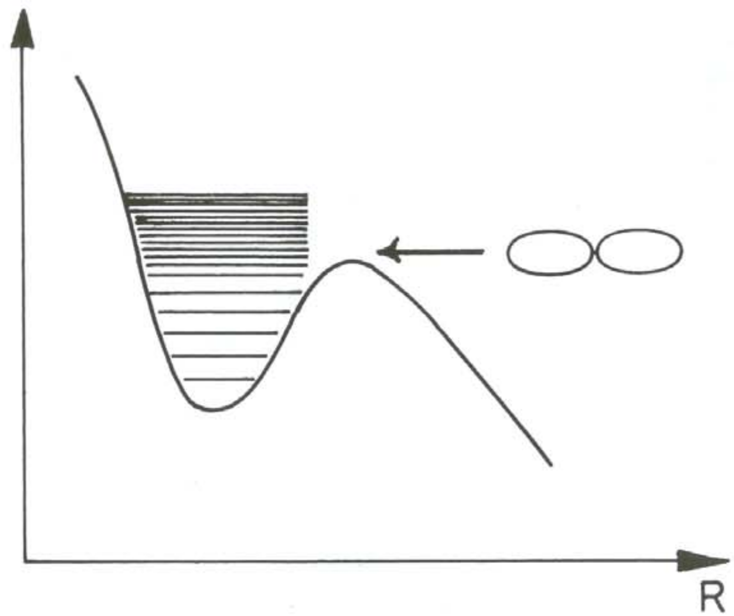
1980

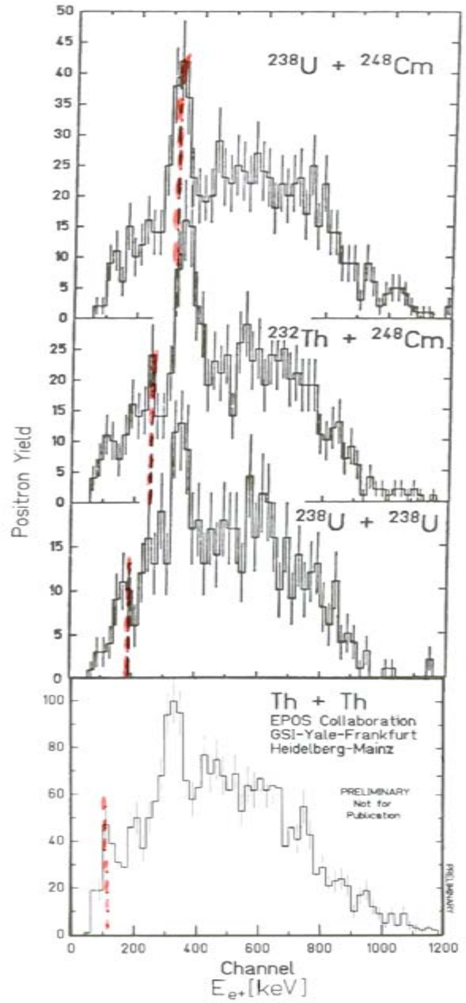
Exp.: Greenberg, Schwalm, Backe, Kienle

Theor.: Reinhardt, Müller



1981/82


R

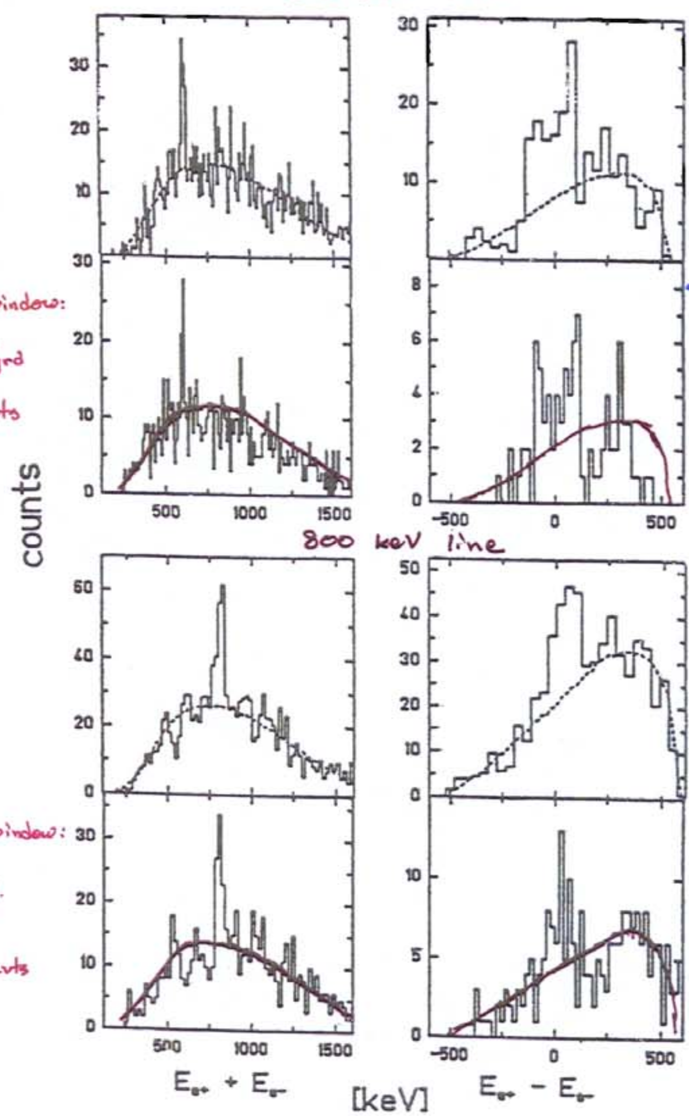


$^{238}U + ^{248}Cm$
$^{232}Th + ^{248}Cm$
$^{238}U + ^{238}U$
Th + Th
EPOS Collaboration
GSI-Yale-Frankfurt
Heidelberg-Mainz
PRELIMINARY
Not for
Publication
Positron Yield
Channel
E_{e^+}[keV]

EPOS U+Th lines reproduced in separate runs

(see H. Bokemeyer, Habilitation)

600 keV line



T. Cowan
Maratea Conf.
Feb. 1986 meas.

Wedge & delay

P. Salabura

June/July 1986

cuts predetermined from above

30 keV window:

61 evts.
33 backgrd

28 ± 8 cts

≃ 3.5 σ

T. Cowan
Maratea Conf.
Feb. 1986 meas.

Wedge

P. Salabura

June/July 1986

80 keV window:

93 evts.
52 bkgd.

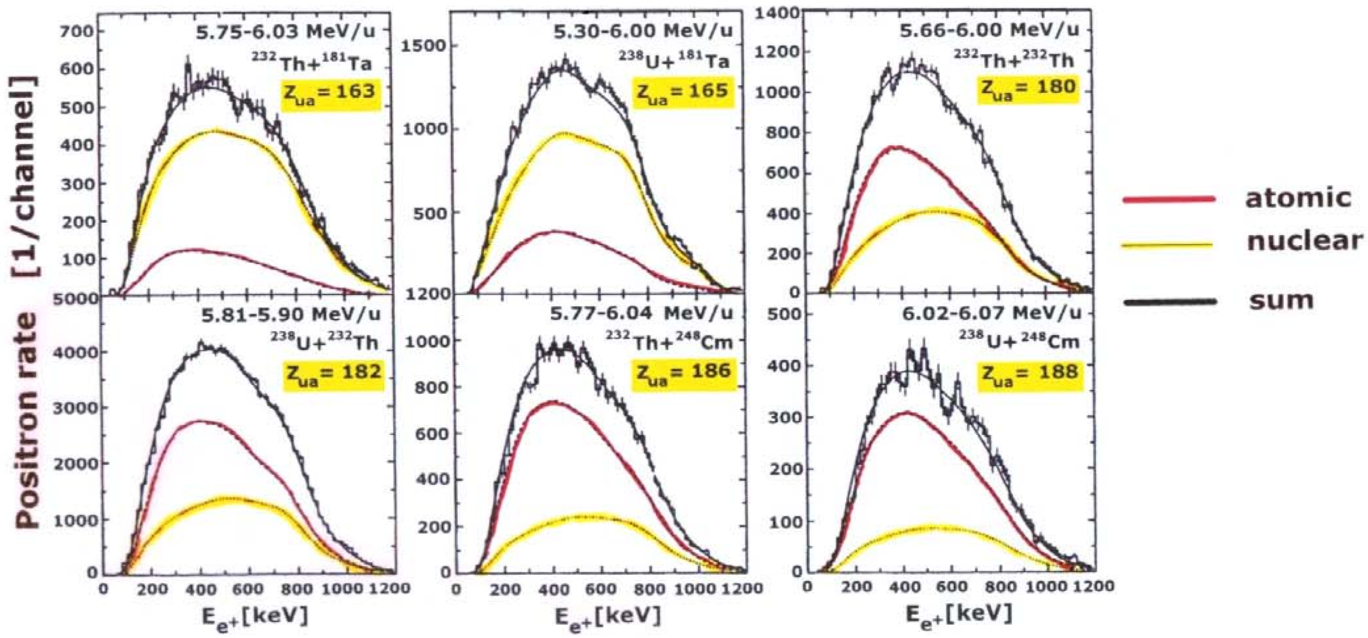
41 ± 10 evts

≃ 4 σ

↘ >2 σ

Synopsis of positron spectra

EPOS
K. Sakaguchi et al. 1989

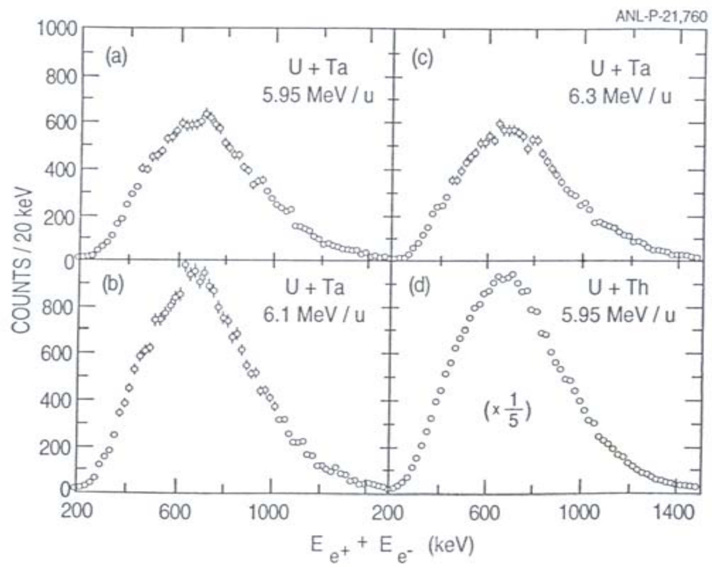


$$\text{Scaling factor} \quad \frac{N_{exp}}{N_{theor}} = \begin{array}{ll} 1.00 \pm 0.05 & \text{EPOS} \\ 0.8 & \text{ORANGE} \\ 0.7 \ldots 1.0 & \text{TORI} \end{array}$$

Adjusted: E1/E2 ratio of pair conversion

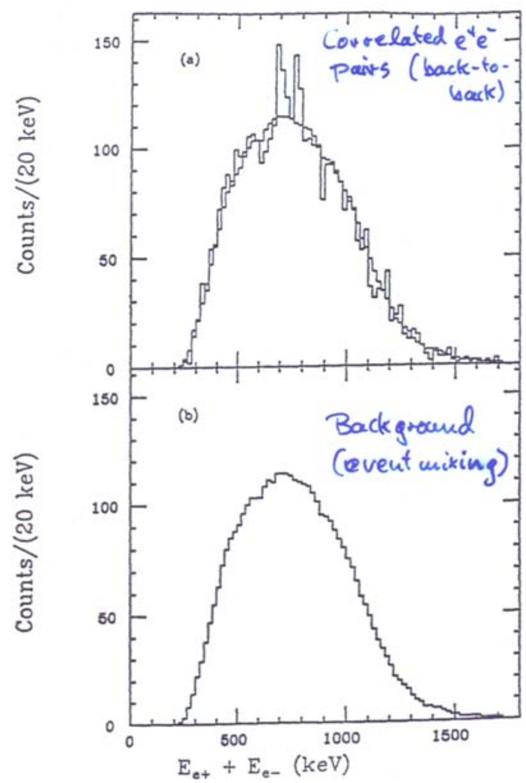
The Argonne Positron Experiment (APEX)

APEX collaboration: I. Ahmad, S. M. Austin, B. B. Back, R. R. Betts, F. P. Calaprice, K. C. Chan, A. Chishti, P. Chowdhury, C. Conner, R. W. Dunford, J. D. Fox, S. J. Freedman, M. Freer, S. B. Gazes, A. L. Hallin, T. Happ, D. Henderson, N. I. Kaloskamis, E. Kashy, W. Kutschera, J. Last, C. J. Lister, M. Liu, M. R. Maier, D. J. Mercer, D. Mikolas, P. A. A. Perera, M. D. Rhein, D. E. Roa, J. P. Schiffer, T. A. Trainor, P. Wilt, J. S. Winfield, M. Wolanski, F. L. H. Wolfs, A. H. Wuosmaa, G. Xu, A. Young, J. E. Yurkon



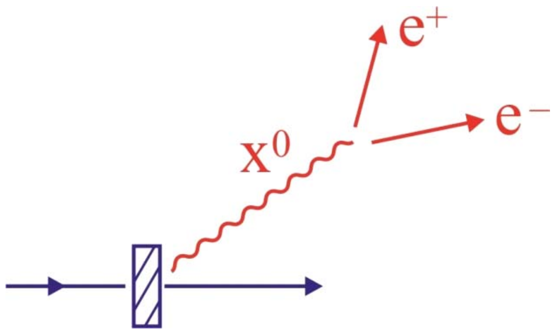
"No evidence for sharp structures"

The APEX pair spetrum (dissenting view)



Data analysis by J. S. Greenberg

A new elementary particle ?



$m_x = 2(m_e+E_{e+})$
≈ 1.68 MeV

Interaction

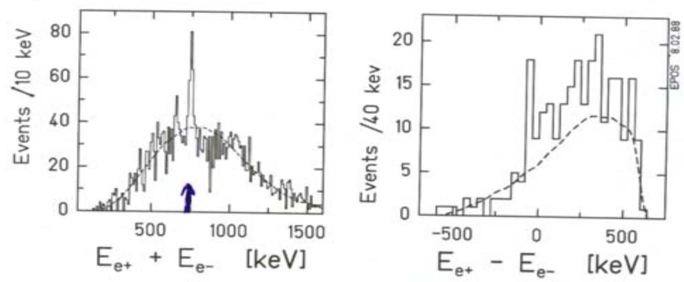
$$L_{e+e-} = G_e \overline{\Psi}_e \Gamma \Psi_e \Phi_\chi$$
$$L_N = G_N \overline{\Psi}_N \Gamma \Psi_N \Phi_\chi$$

$\overline{\Psi}_e$ = electron-positron field
$\overline{\Psi}_N$ = nuclear (quark) field

$\Gamma_S = 1$	scalar
$\Gamma_P = \gamma_5$	pseudo scalar
$\Gamma_V = \gamma_\mu$	vector
$\Gamma_A = \gamma_\mu \gamma_5$	pseudo vector
$\Gamma_T = \sigma_{\mu V}$	tensor

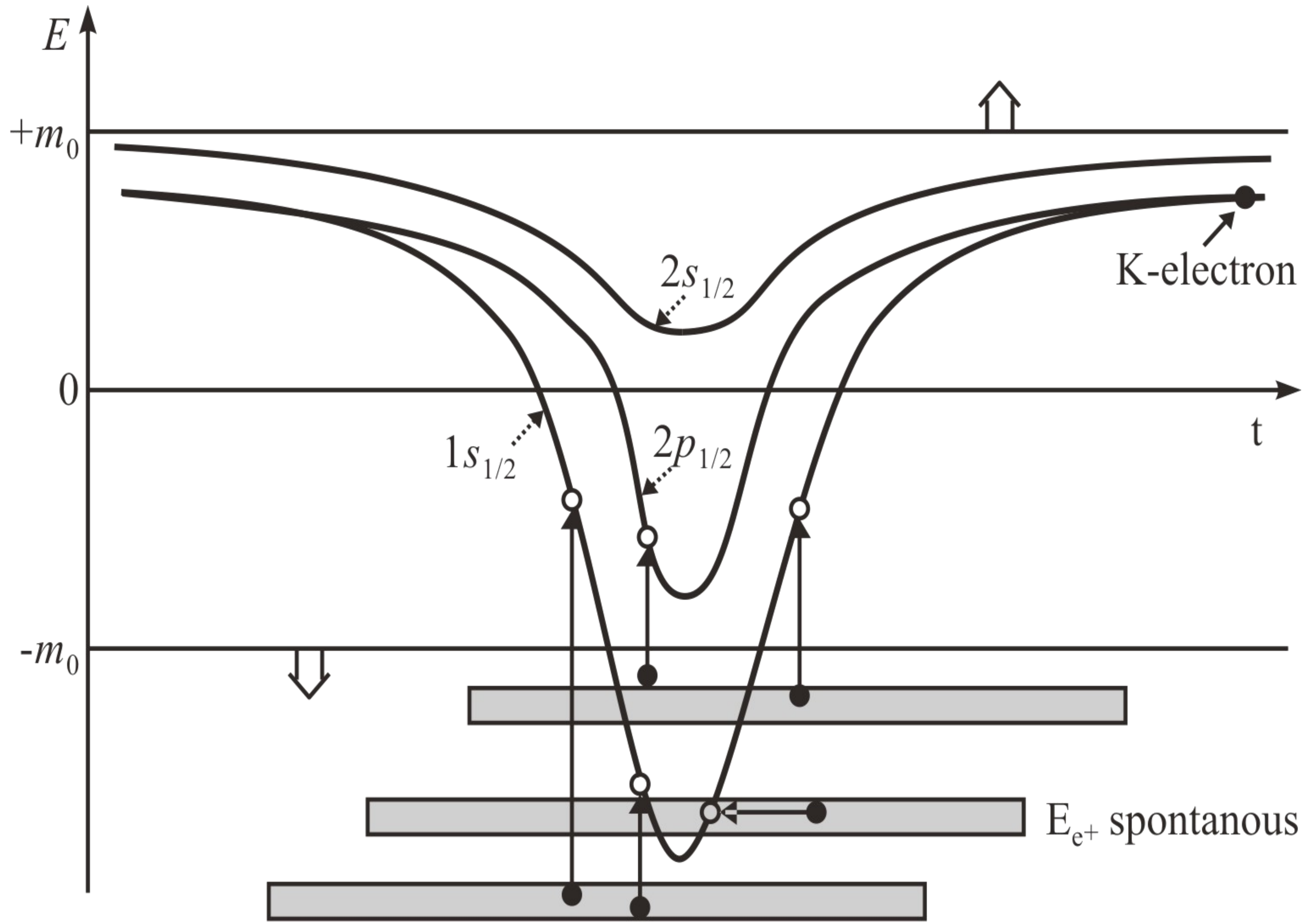
U + Ta

748 keV line



Epos

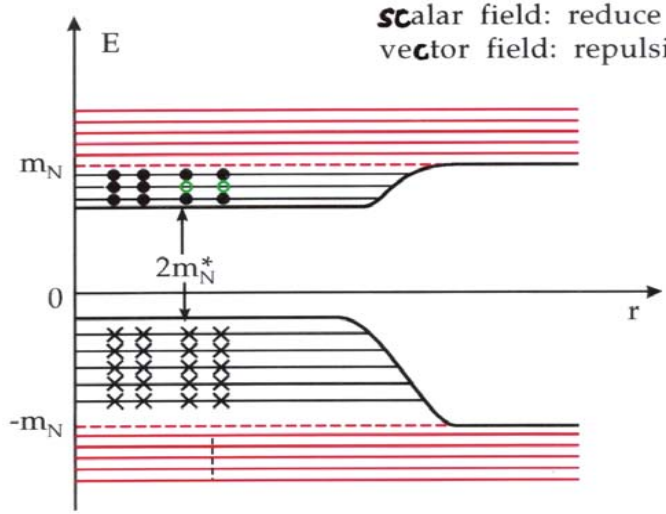
Spring/Summer 1988

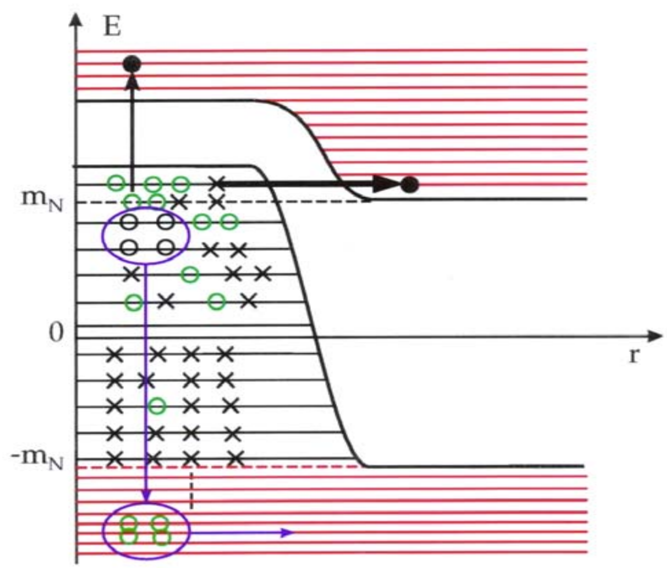


E
$+m_0$
0
$-m_0$
t
$2s_{1/2}$
$1s_{1/2}$
$2p_{1/2}$
K-electron
E_{e^+} spontanous

Mishustin , Satarov ,
Greiner 1990- 1992

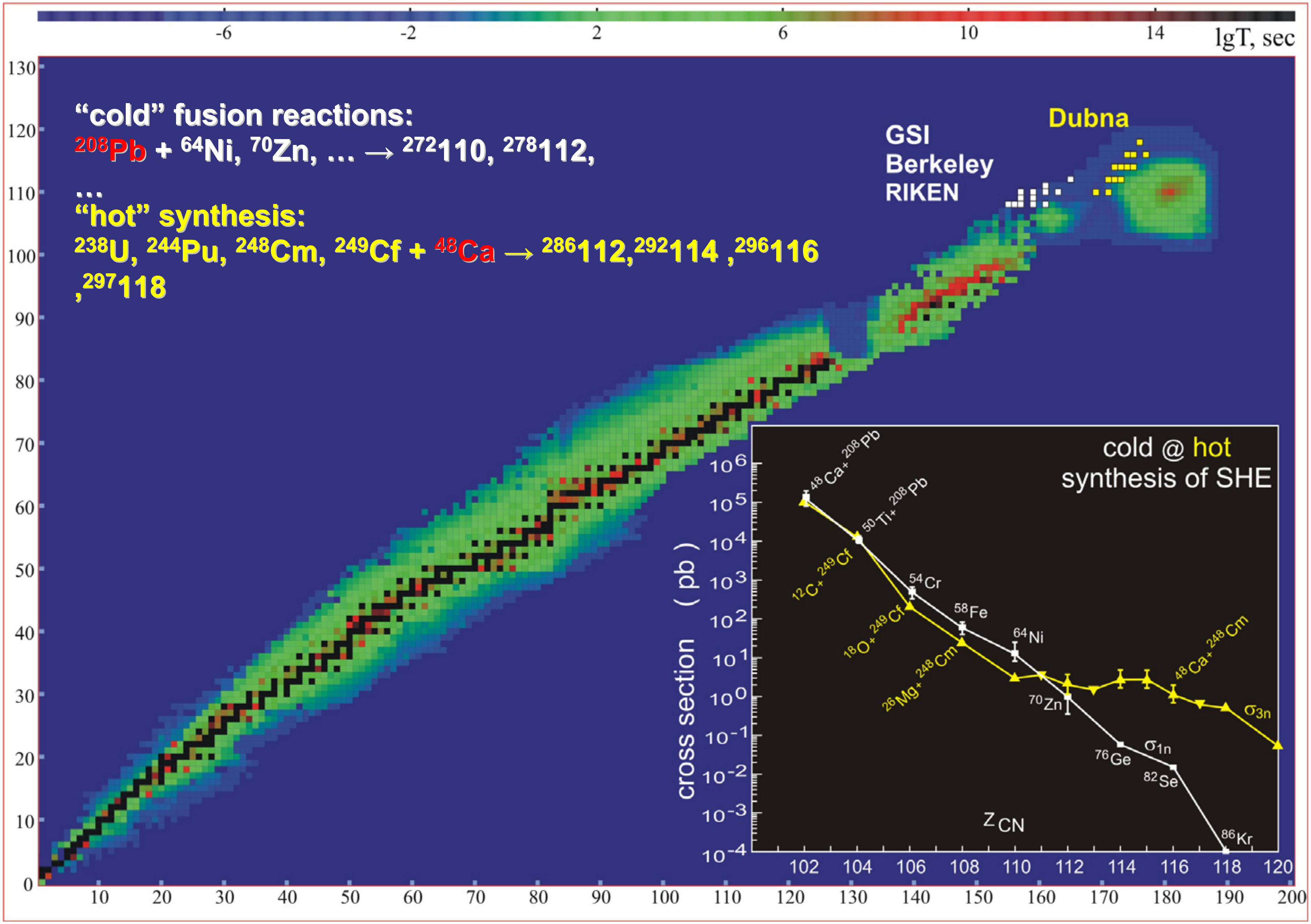
scalar field: reduce nucleon mass (attr.)
vector field: repulsive potential ($\pm\ \bar{p}$)



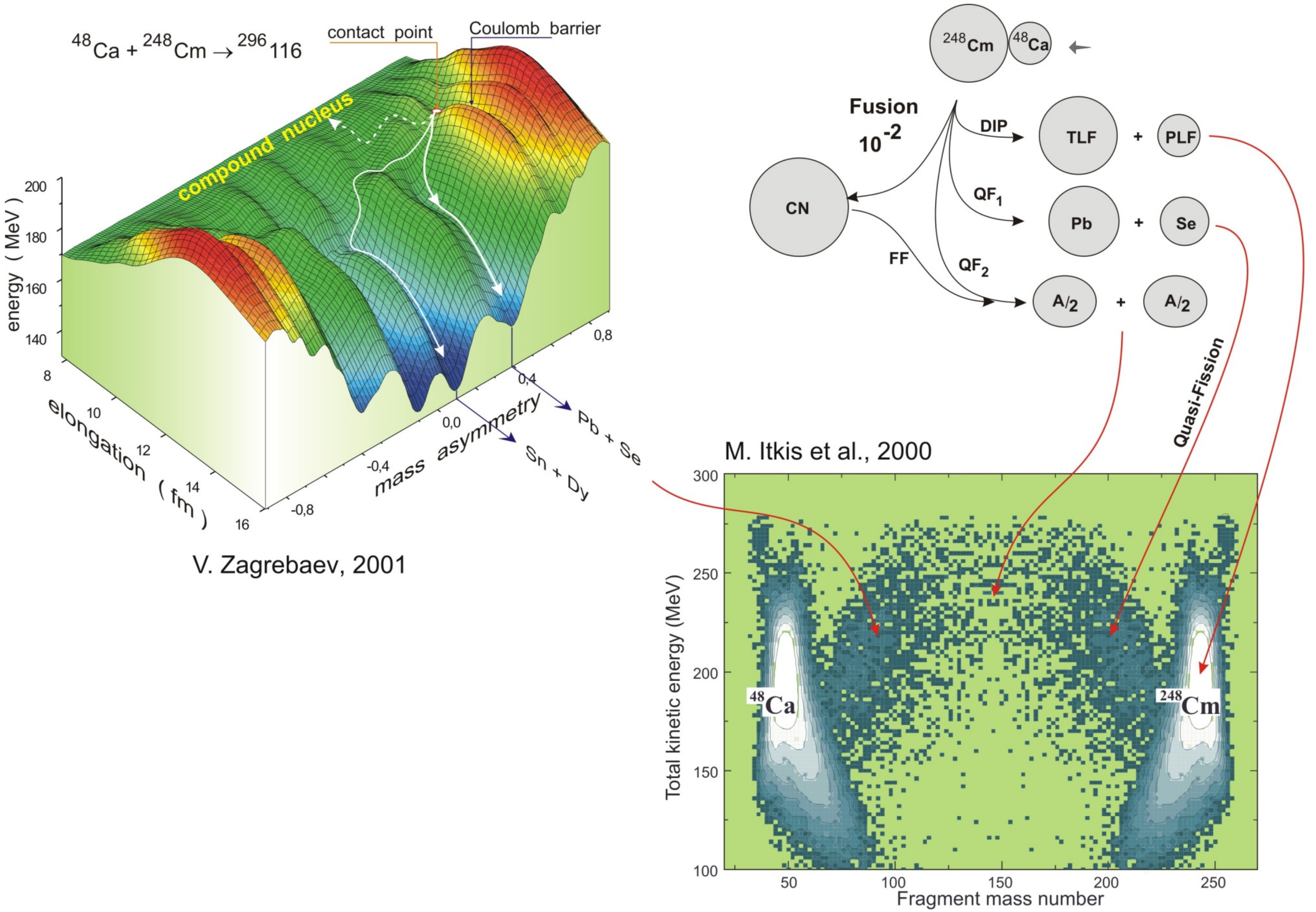


Antimatter - Cluster - Production out of the correlated vacuum!!

On the way to the first Island of Stability

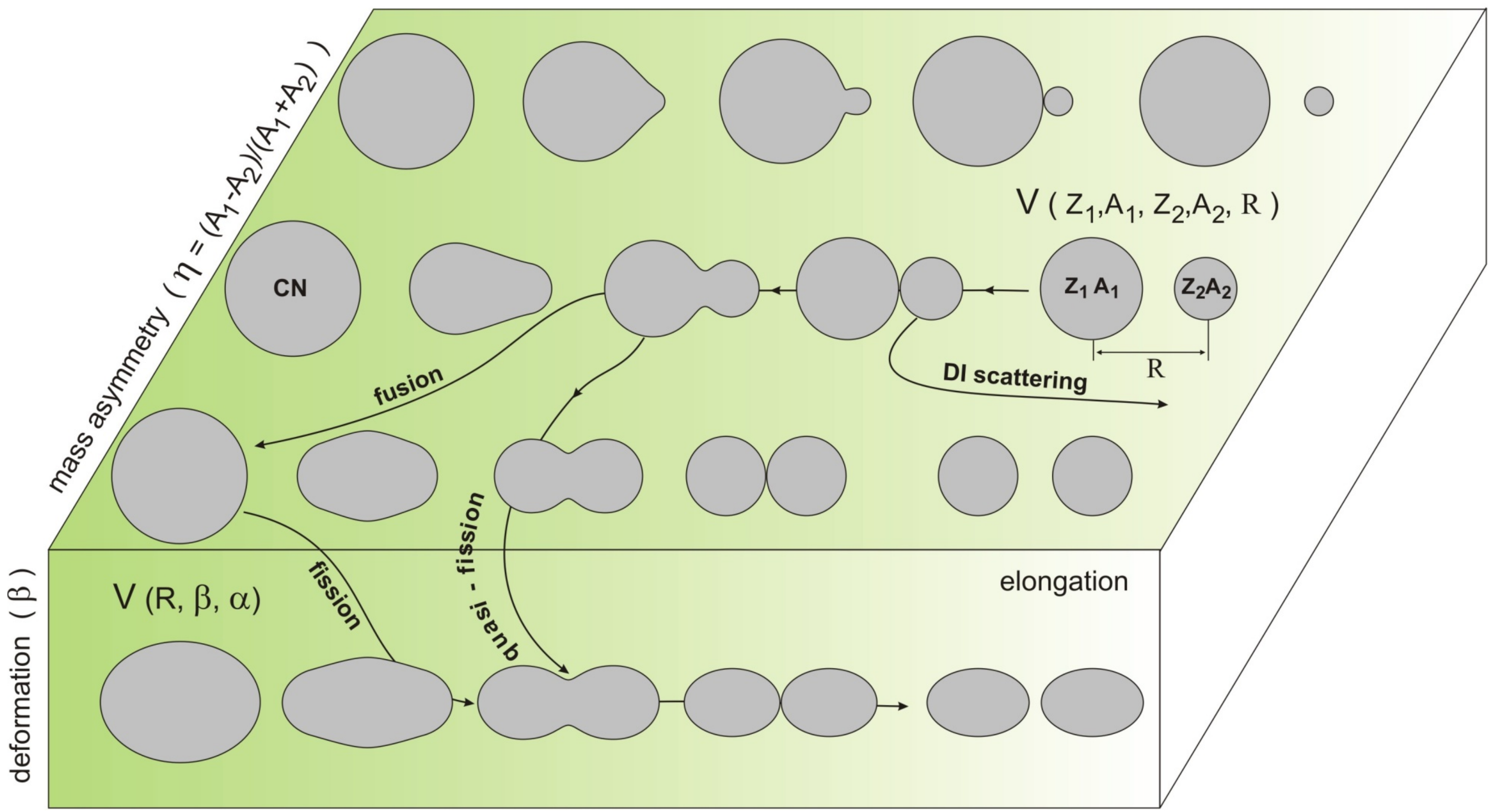


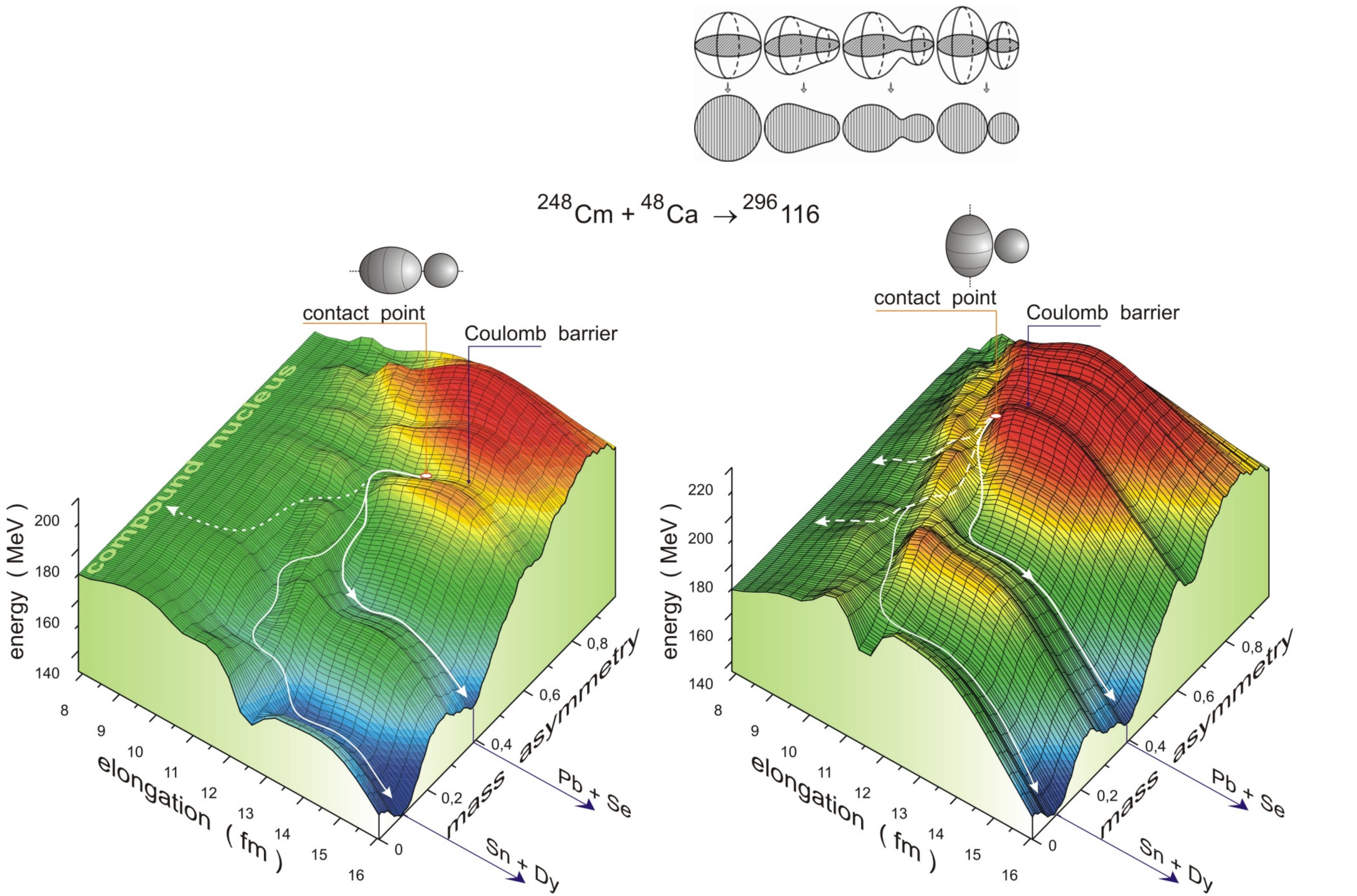
Strongly coupled
Deep Inelastic, Quasi-Fission, and Fusion-Fission processes



principal degrees of freedom: $\{ q_1, q_2, ...\}$,
potential energy surface: $V(q_1,q_2,...)$,
dynamic equations of motion: $dq_i / dt = ...$

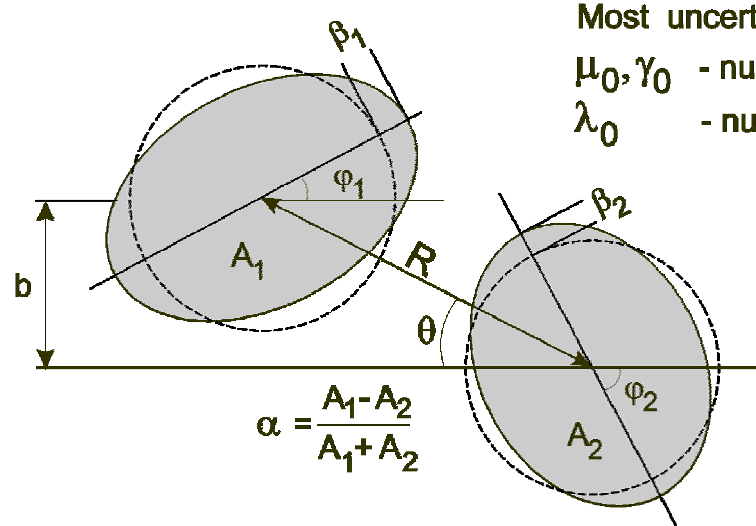
Unified for all the processes:
Deep Inelastic, Quasi-Fission and Fusion-Fission !!!





$^{248}Cm + ^{48}Ca \rightarrow ^{296}116$
contact point
Coulomb barrier
compound nucleus
energy (MeV)
200
180
160
140
elongation (fm)
8
9
10
11
12
13
14
15
16
mass asymmetry
0
0,2
0,4
0,6
0,8
Pb + Se
Sn + Dy
contact point
Coulomb barrier
energy (MeV)
220
200
180
160
140
elongation (fm)
8
9
10
11
12
13
14
15
16
mass asymmetry
0
0,2
0,4
0,6
0,8
Pb + Se
Sn + Dy

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \alpha\}$



Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

$$\frac{d\vartheta}{dt} = \frac{\hbar \ell}{\mu_R R^2}$$

$$\frac{d\varphi_1}{dt} = \frac{\hbar L_1}{\Im_1}$$

$$\frac{d\varphi_2}{dt} = \frac{\hbar L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta_1}}{\mu_{\beta_1}}$$

$$\frac{d\beta_2}{dt} = \frac{p_{\beta_2}}{\mu_{\beta_2}}$$

$$\frac{d\alpha}{dt} = \frac{2}{A_{CN}} D_A^{(1)}(\alpha) + \frac{2}{A_{CN}} \sqrt{D_A^{(2)}(\alpha)} \Gamma_\alpha(t)$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\hbar^2 \ell^2}{\mu_R R^3} + \left(\frac{\hbar^2 \ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right) \frac{\partial \mu_R}{\partial R} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2} \frac{\partial \mu_{\beta_1}}{\partial R} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2} \frac{\partial \mu_{\beta_2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T} \Gamma_R(t)$$

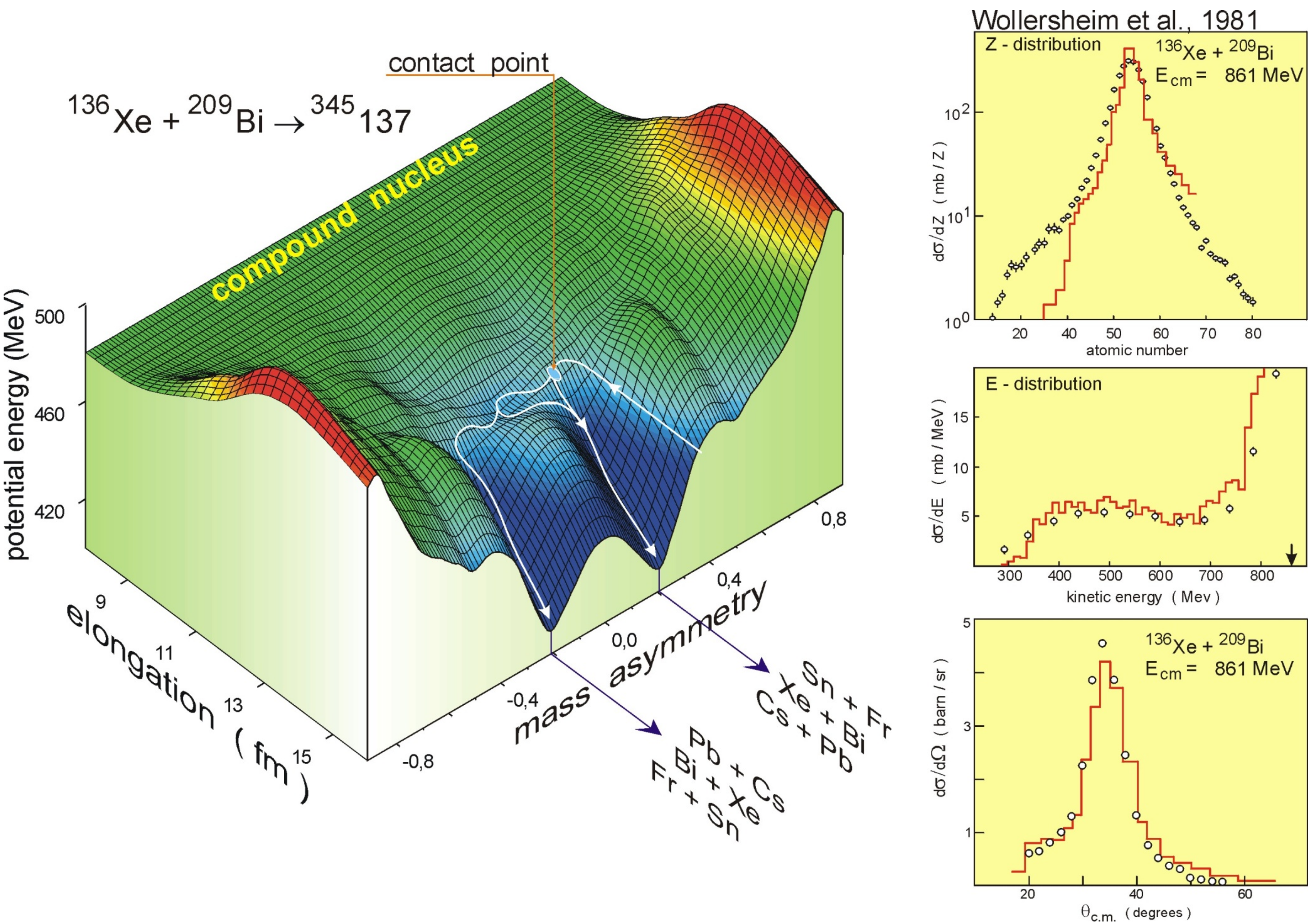
$$\frac{d\ell}{dt} = -\frac{1}{\hbar} \frac{\partial V}{\partial \vartheta} - \gamma_{\rm tang} \left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2 \right) R + \frac{R}{\hbar} \sqrt{\gamma_{\rm tang} T} \Gamma_{\rm tang}(t)$$

$$\frac{dL_1}{dt} = -\frac{1}{\hbar} \frac{\partial V}{\partial \varphi_1} + \gamma_{\rm tang} \left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2 \right) a_1 - \frac{a_1}{\hbar} \sqrt{\gamma_{\rm tang} T} \Gamma_{\rm tang}(t)$$

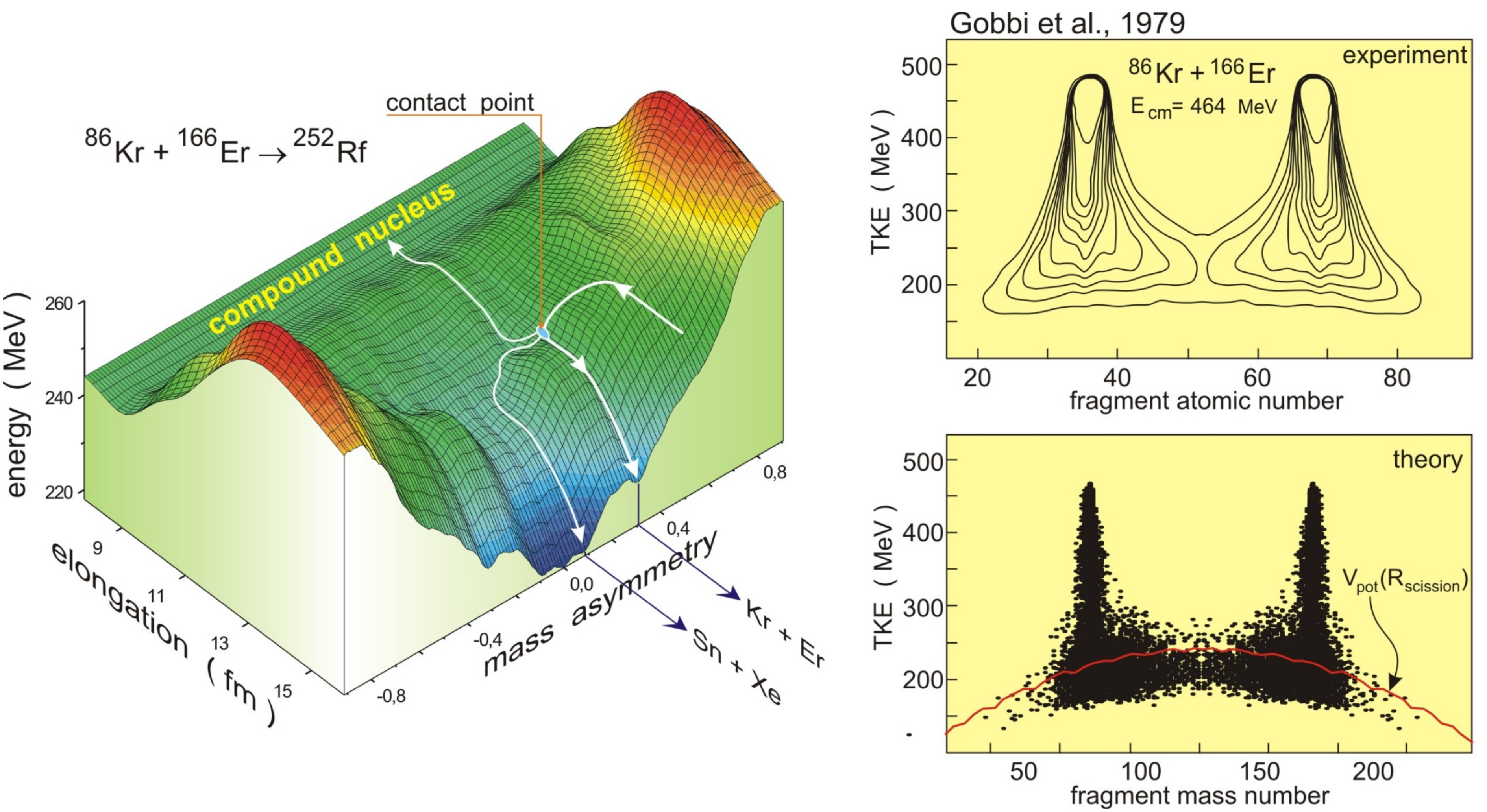
$$\frac{dL_2}{dt} = -\frac{1}{\hbar} \frac{\partial V}{\partial \varphi_2} + \gamma_{\rm tang} \left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2 \right) a_2 - \frac{a_2}{\hbar} \sqrt{\gamma_{\rm tang} T} \Gamma_{\rm tang}(t)$$

$$\frac{dp_{\beta_1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2} \frac{\partial \mu_{\beta_1}}{\partial \beta_1} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2} \frac{\partial \mu_{\beta_2}}{\partial \beta_1} + \frac{\hbar^2 L_1^2}{2\Im_1^2} \frac{\partial \Im_1}{\partial \beta_1} + \left(\frac{\hbar^2 \ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right) \frac{\partial \mu_R}{\partial \beta_1} - \gamma_{\beta_1} \frac{p_{\beta_1}}{\mu_{\beta_1}} + \sqrt{\gamma_{\beta_1} T} \Gamma_{\beta_1}(t)$$

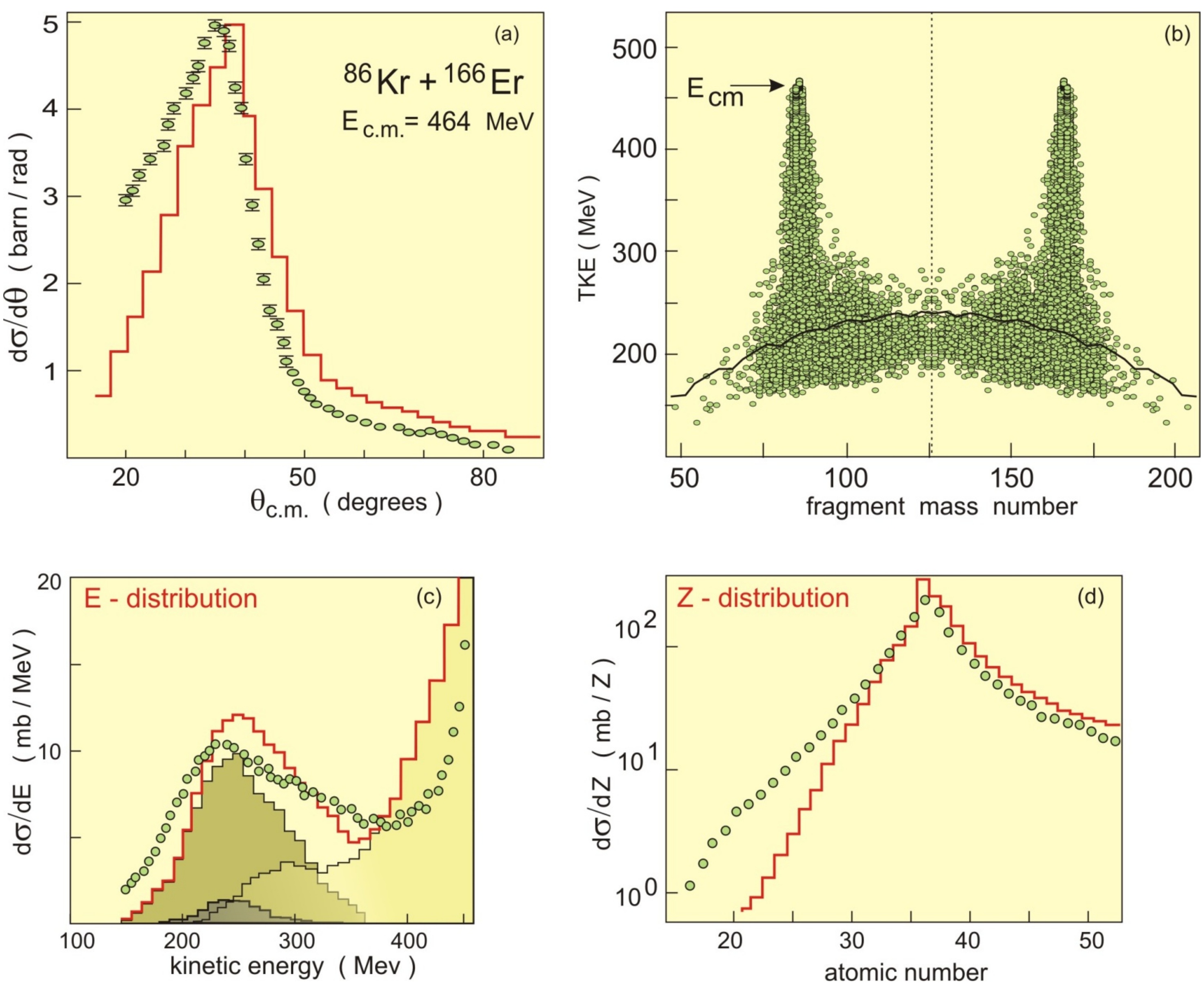
$$\frac{dp_{\beta_2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2} \frac{\partial \mu_{\beta_1}}{\partial \beta_2} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2} \frac{\partial \mu_{\beta_2}}{\partial \beta_2} + \frac{\hbar^2 L_2^2}{2\Im_2^2} \frac{\partial \Im_2}{\partial \beta_2} + \left(\frac{\hbar^2 \ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right) \frac{\partial \mu_R}{\partial \beta_2} - \gamma_{\beta_2} \frac{p_{\beta_2}}{\mu_{\beta_2}} + \sqrt{\gamma_{\beta_2} T} \Gamma_{\beta_2}(t).$$



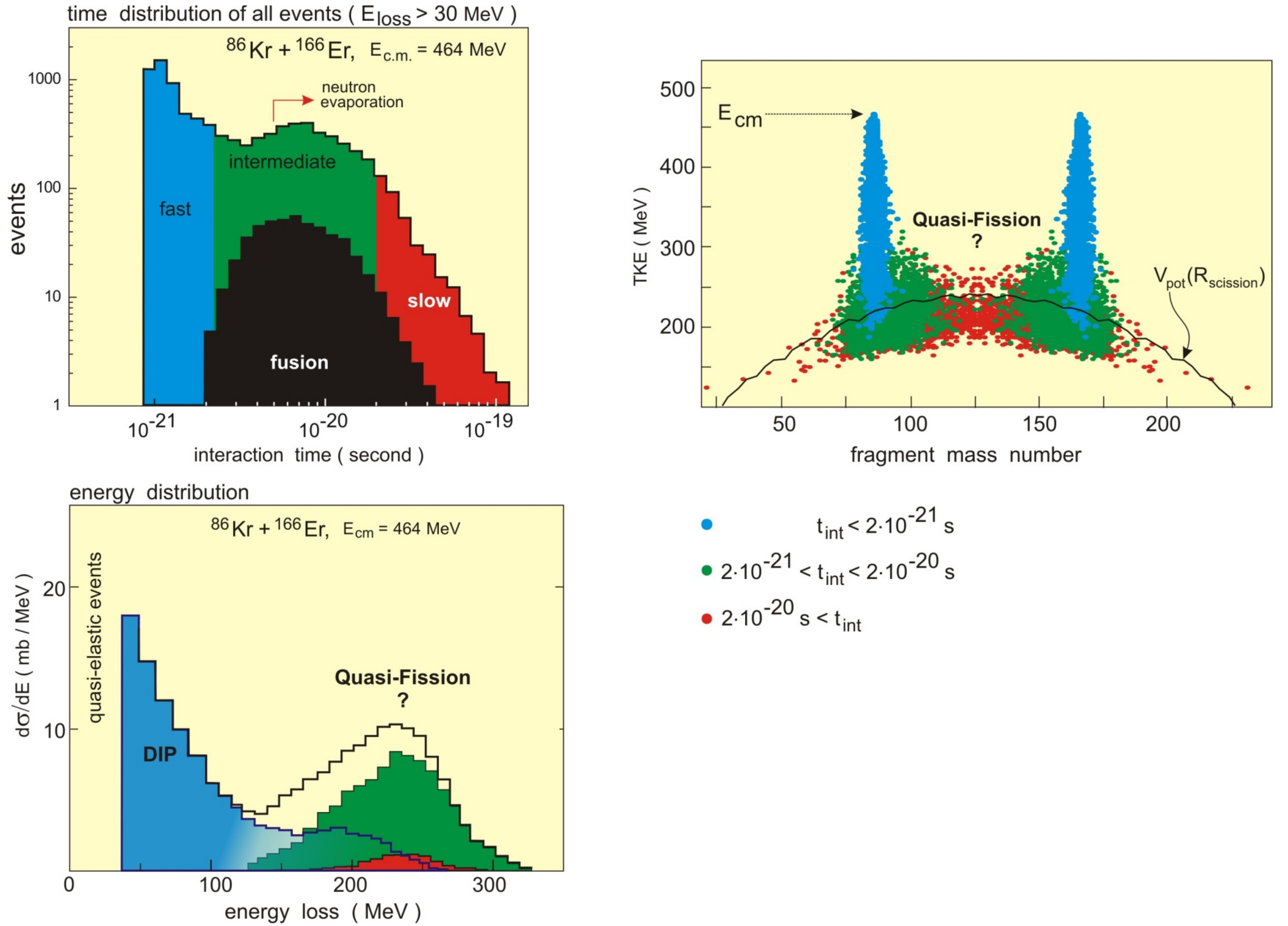
136Xe + 209Bi → 345137
contact point
compound nucleus
potential energy (MeV)
500
460
420
elongation (fm)
9
11
13
15
mass asymmetry
-0,8
-0,4
0,0
0,4
0,8
Pb + Cs
Bi + Xe
Fr + Sn
Sn + Fr
Xe + Bi
Cs + Pb
Wollersheim et al., 1981
Z - distribution
136Xe + 209Bi
Ecm = 861 MeV
dσ/dZ (mb / Z)
10^0
10^1
10^2
20
40
50
60
70
80
atomic number
E - distribution
dσ/dE (mb / MeV)
5
10
15
300
400
500
600
700
800
kinetic energy (Mev)
136Xe + 209Bi
Ecm = 861 MeV
dσ/dΩ (barn / sr)
1
3
5
20
40
60
θc.m. (degrees)



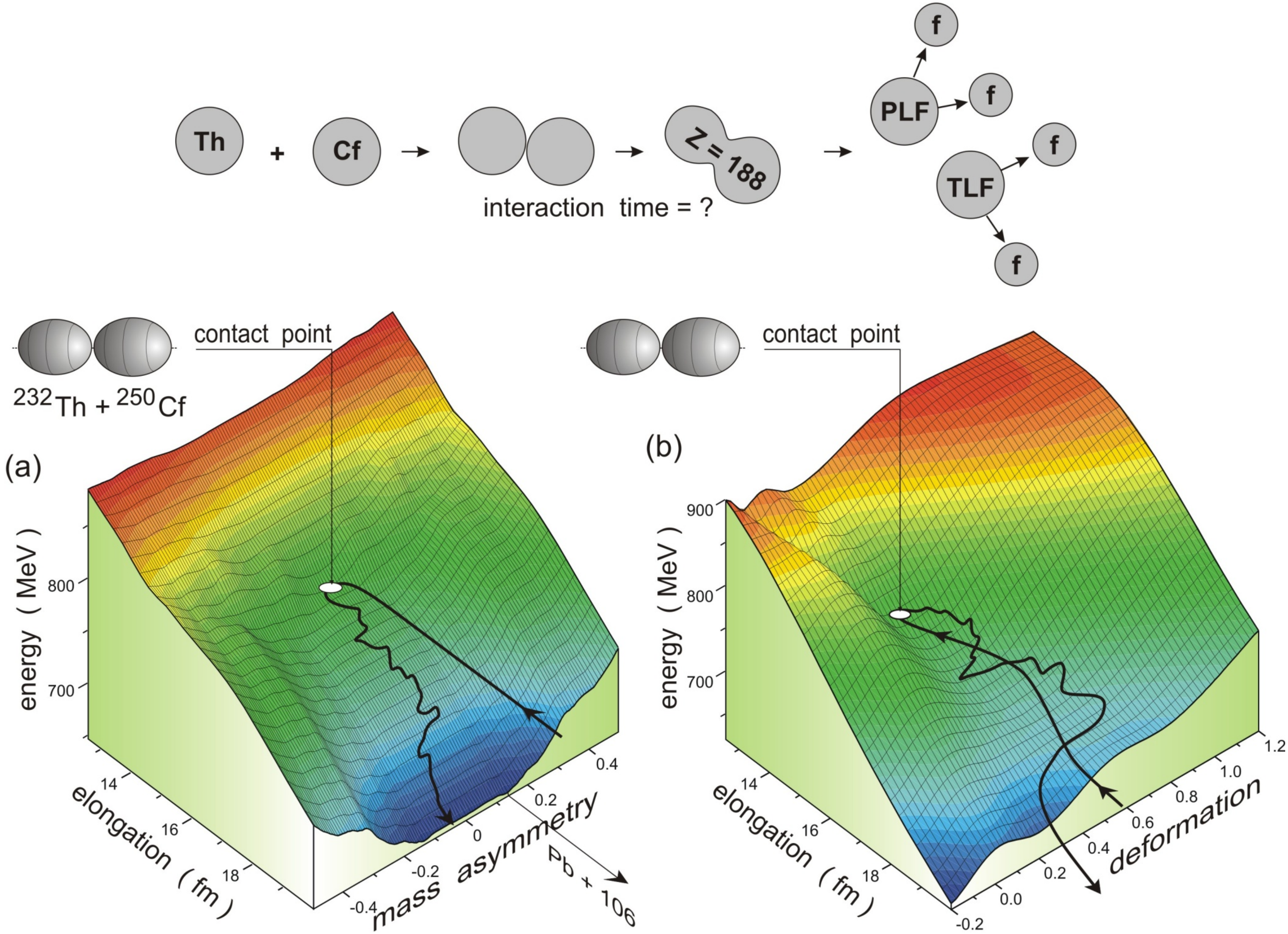
$^{86}Kr + ^{166}Er \rightarrow ^{252}Rf$
contact point
compound nucleus
energy (MeV)
260
240
220
elongation (fm)
9
11
13
15
mass asymmetry
-0,8
-0,4
0,0
0,4
0,8
Sn + Xe
Kr + Er
Gobbi et al., 1979
experiment
$^{86}Kr + ^{166}Er$
E_{cm}= 464 MeV
TKE (MeV)
500
400
300
200
20
40
60
80
fragment atomic number
theory
$V_{pot}(R_{scission})$
50
100
150
200
fragment mass number

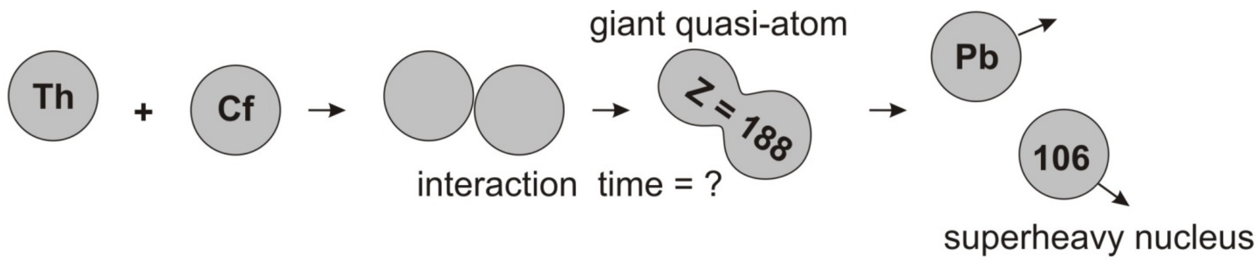


(a)
^{86}Kr + ^{166}Er
E$_{c.m.}$= 464 MeV
dσ/dθ (barn / rad)
θ$_{c.m.}$ (degrees)
(b)
E$_{cm}$
TKE (MeV)
fragment mass number
(c)
E - distribution
dσ/dE (mb / MeV)
kinetic energy (Mev)
(d)
Z - distribution
dσ/dZ (mb / Z)
atomic number

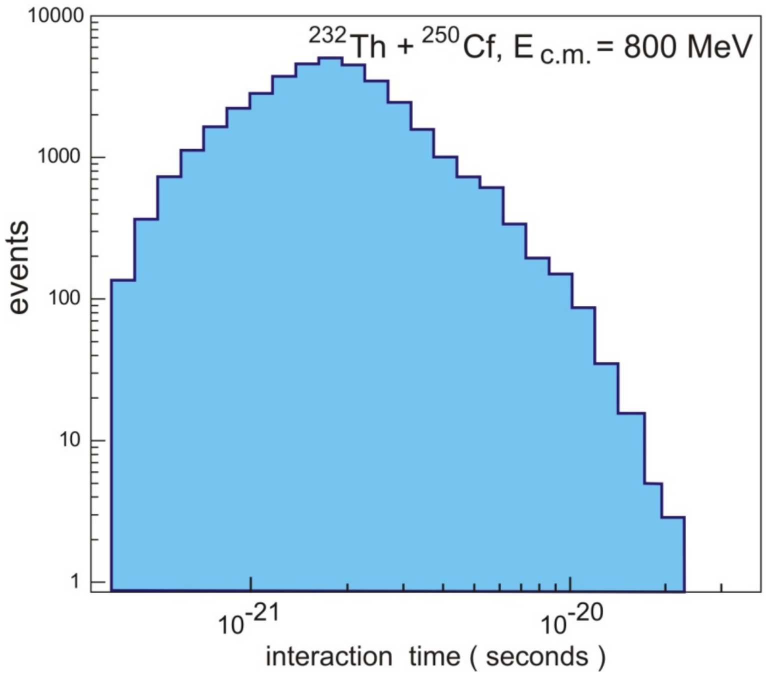


time distribution of all events (E loss > 30 MeV)
86 Kr + 166 Er, E c.m. = 464 MeV
1000
100
10
1
events
neutron
evaporation
intermediate
fast
slow
fusion
10-21
10-20
10-19
interaction time (second)
500
400
300
200
TKE (MeV)
E cm
Quasi-Fission
?
V pot(R scission)
50
100
150
200
fragment mass number
t int < 2·10-21 s
2·10-21 < t int < 2·10-20 s
2·10-20 s < t int
energy distribution
86 Kr + 166 Er, E cm = 464 MeV
20
10
dσ/dE (mb / MeV)
quasi-elastic events
DIP
Quasi-Fission
?
0
100
200
300
energy loss (MeV)

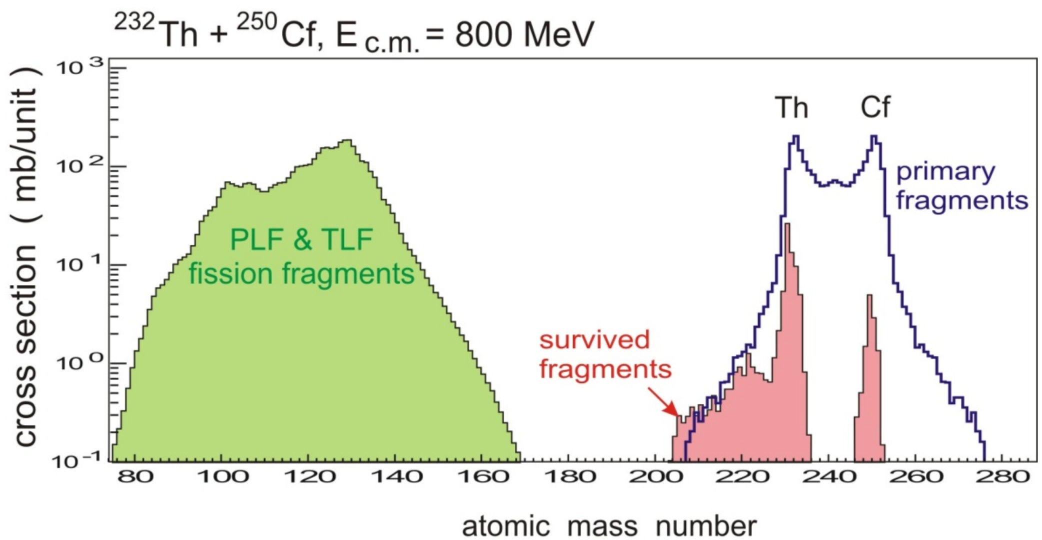

Th
+
Cf
Z = 188
interaction time = ?
PLF
TLF
f
contact point
^{232}Th + ^{250}Cf
(a)
(b)
energy (MeV)
elongation (fm)
mass asymmetry
Pb + 106
deformation
800
700
900
14
16
18
0.4
0.2
0
-0.2
-0.4
1.2
1.0
0.8
0.6
0.0



giant quasi-atom
Th
+
Cf
Z = 188
Pb
106
interaction time = ?
superheavy nucleus

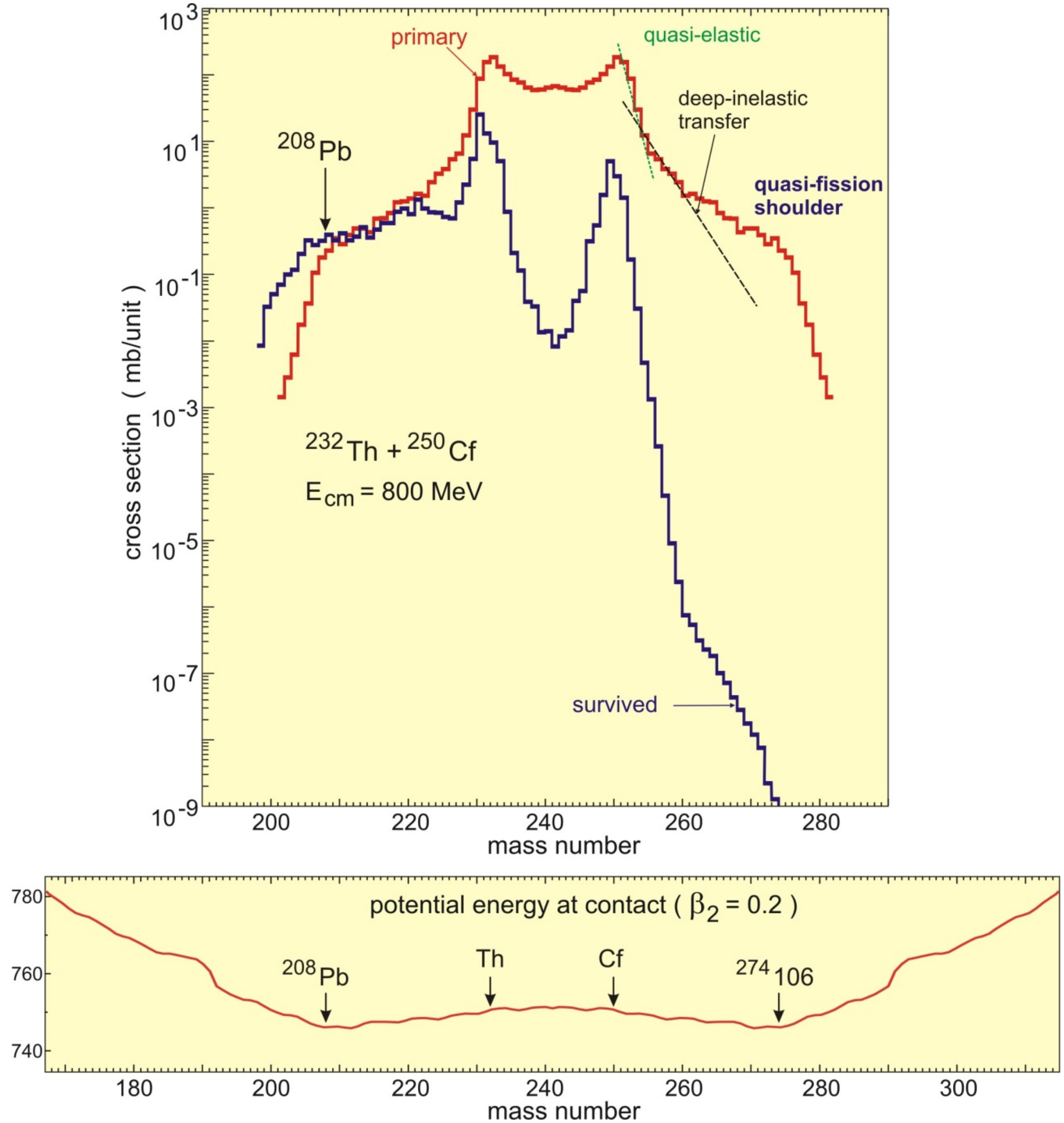


232Th + 250Cf, E c.m. = 800 MeV
events
10000
1000
100
10
1
10-21
10-20
interaction time (seconds)

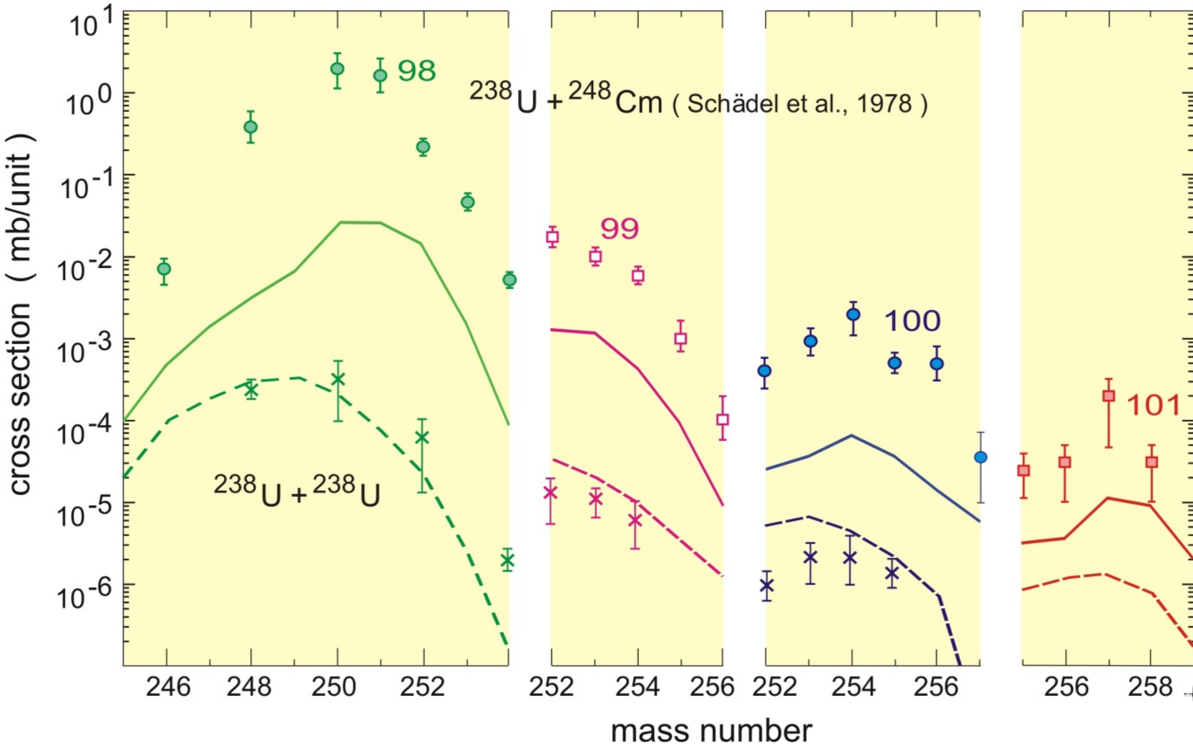


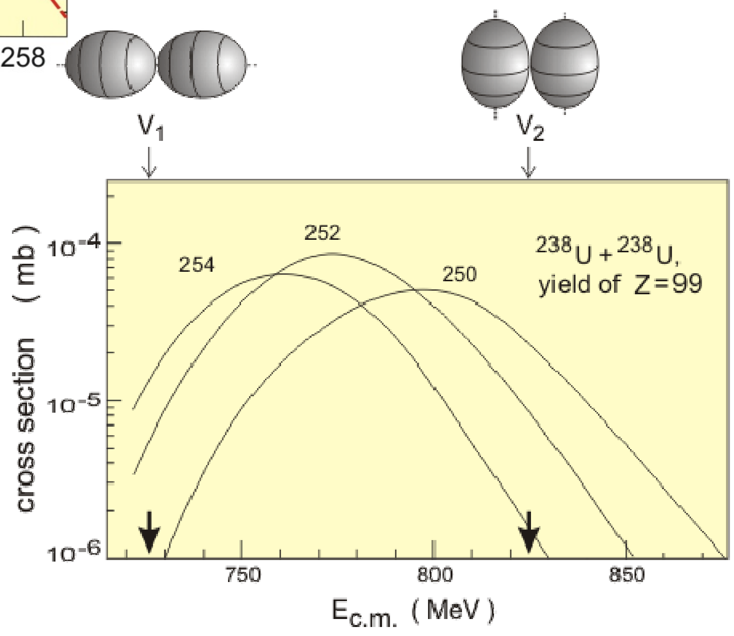
232Th + 250Cf, E c.m. = 800 MeV
cross section (mb/unit)
10 3
10 2
10 1
10 0
10 -1
Th
Cf
primary fragments
PLF & TLF fission fragments
survived fragments
80
100
120
140
160
180
200
220
240
260
280
atomic mass number

Deep-Inelastic and Quasi-Fission processes in heavy-ion damped collisions

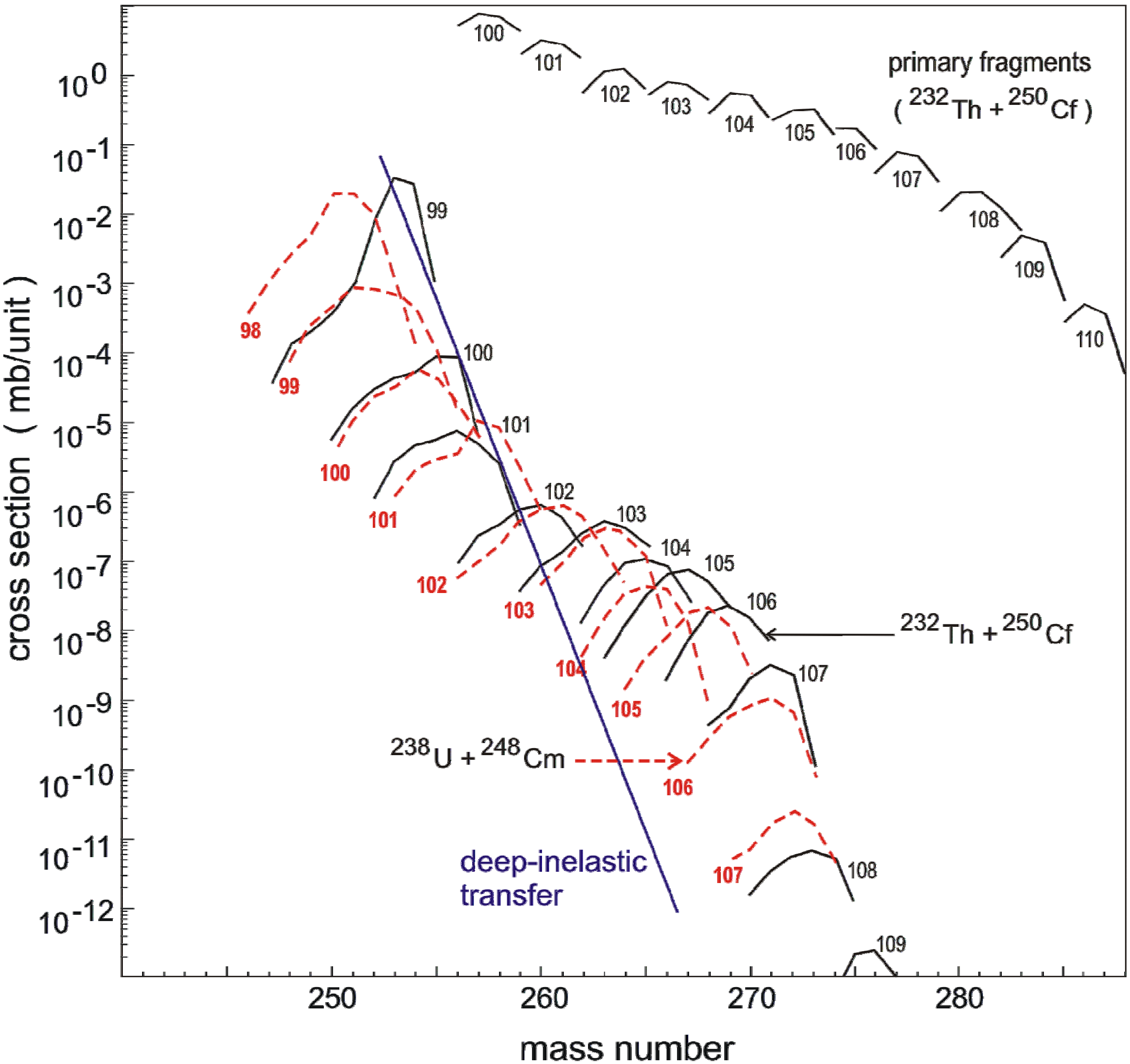


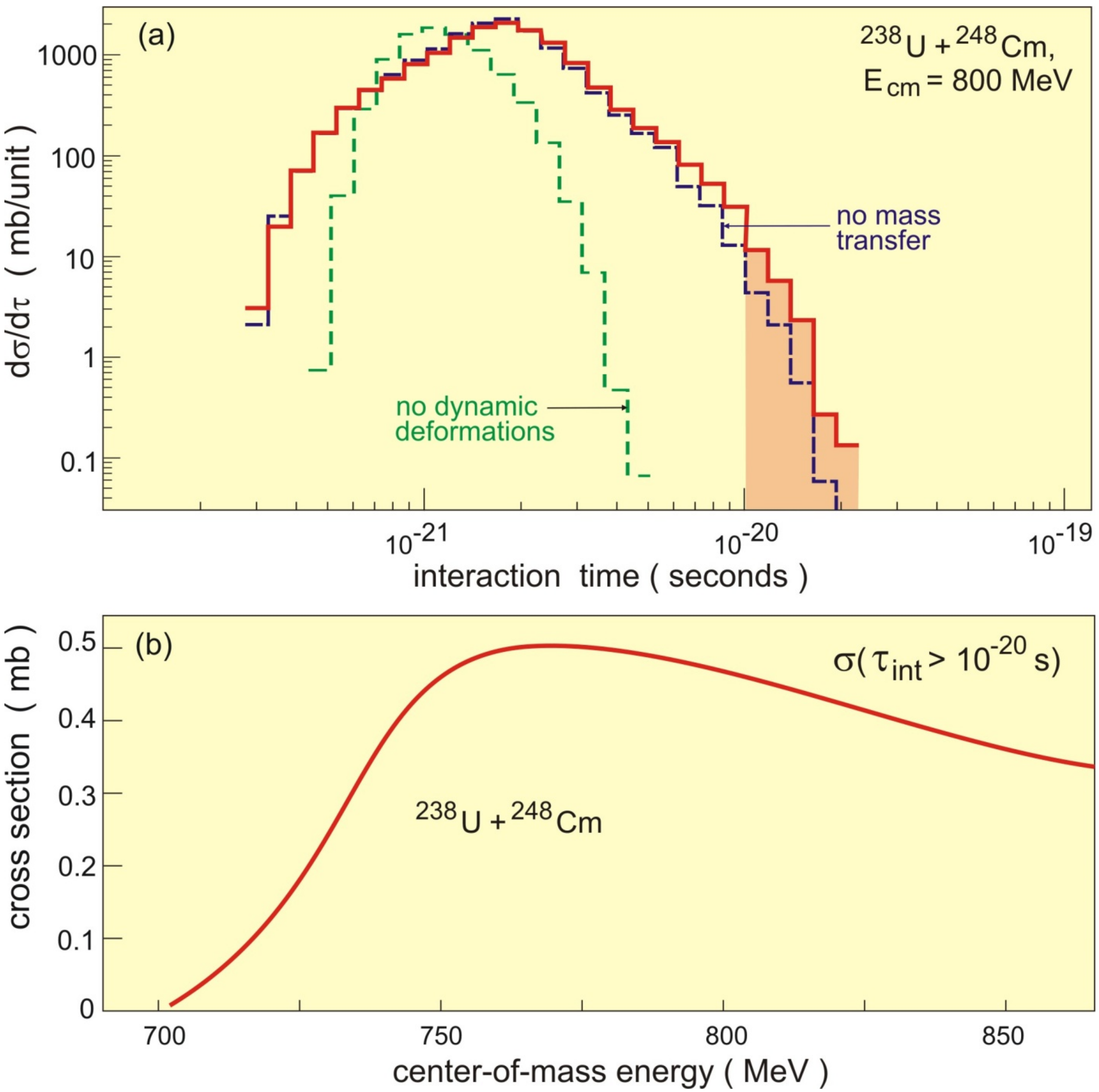
Comparison with available experimental data





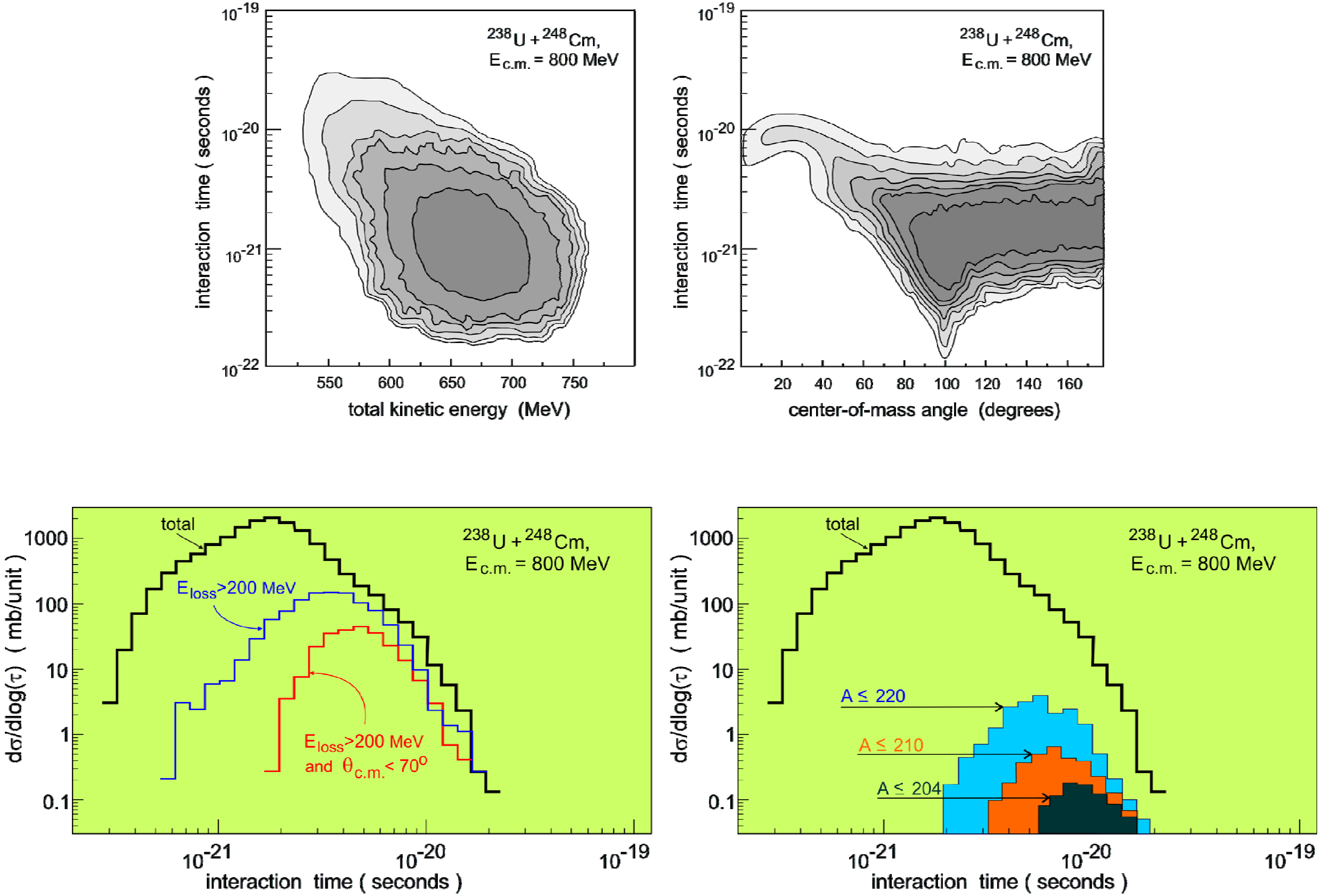
Isotopic yield of SHE in collisions of transactinides

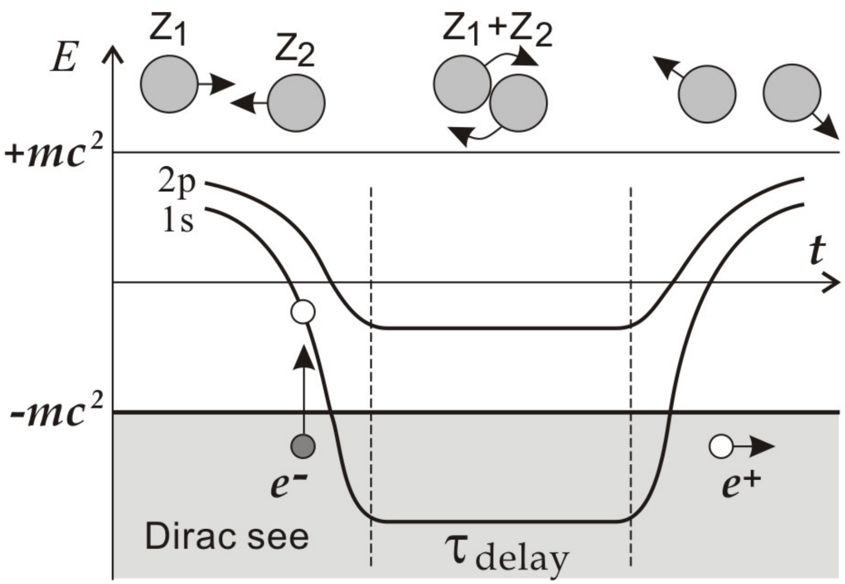


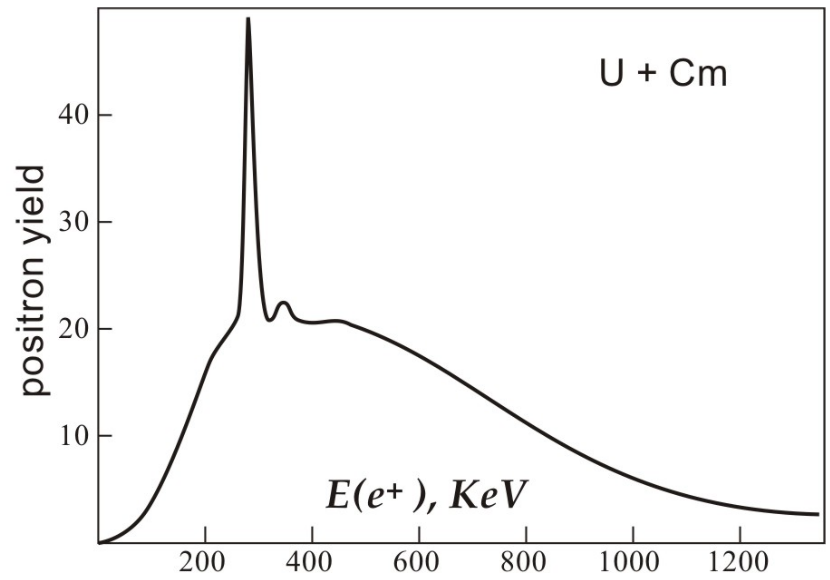


(a)
^{238}U + ^{248}Cm,
E$_{cm}$ = 800 MeV
1000
100
10
1
0.1
dσ/dτ (mb/unit)
no mass
transfer
no dynamic
deformations
10^{-21}
10^{-20}
10^{-19}
interaction time (seconds)
(b)
σ(τ$_{int}$ > 10^{-20} s)
0.5
0.4
0.3
0.2
0.1
0
cross section (mb)
^{238}U + ^{248}Cm
700
750
800
850
center-of-mass energy (MeV)

What are the triggers for a long reaction time ?







Greiner,
Reinhardt, 1981