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Joint Institute for Nuclear Research, Dubna, Russia

Appearance of Nuclear Shell Effects and Initial Charge (Mass) Asymmetry in Formation of Products in Heavy Ion Collisions

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Content

- Introduction
- Main mechanisms of heavy ion of collisions at low energies.
- Reason causing the hindrance of complete fusion
- Peculiarities of dinuclear system model
- The ways of searching optimal conditions for the synthesis of superheavy elements.
- Conclusions

Introduction

For light or medium-heavy systems, capture inside the Coulomb barrier leads invariably to fusion, so that the capture (or barrier-passing) cross-section coincides with the complete fusion cross-section. Total fusion implies the formation of the compound nucleus. However, for heavy systems capture inside the barrier, i.e. formation of a dinucleus, is not a sufficient condition for fusion. The dinucleus system may reseparate into two fragments before that full equilibration of all degrees of freedom has been reached. Consequently, a considerable part of the total capture cross-section goes to the quasi-fission channel. This phenomenon is experimentally observed as a hindrance to fusion .

For the light dinuclear system leading to compound nucleus with high fission barrier the measurement of the evaporation residues allows us to find directly fusion cross section:

Capture=Quasifission + Fusion-Fission + Fast-fission + Evaporation residues

Because for light system Capture=Fuison= Evaporation residues.

Achievements in synthesis of superheavy elements

Nuclear centers/ Elements	SHIP-GSI, Darmstadt	Flerov Lab. JINR-Dubna	RIKEN, Japan	Lawrence Berkeley Lab.
Z=110	Darmstadtium		Confirmed	
Z=111	Roentgenium		Confirmed	
Z=112	Copernicium		Confirmed	
Z=113			***Synthesized***	
Z=114		***Synthesized***		Confirmed
Z=115		***Synthesized***		
Z=116	Confirmed !	***Synthesized***		
Z=117		***Synthesized***		
Z=118		***Synthesized***		

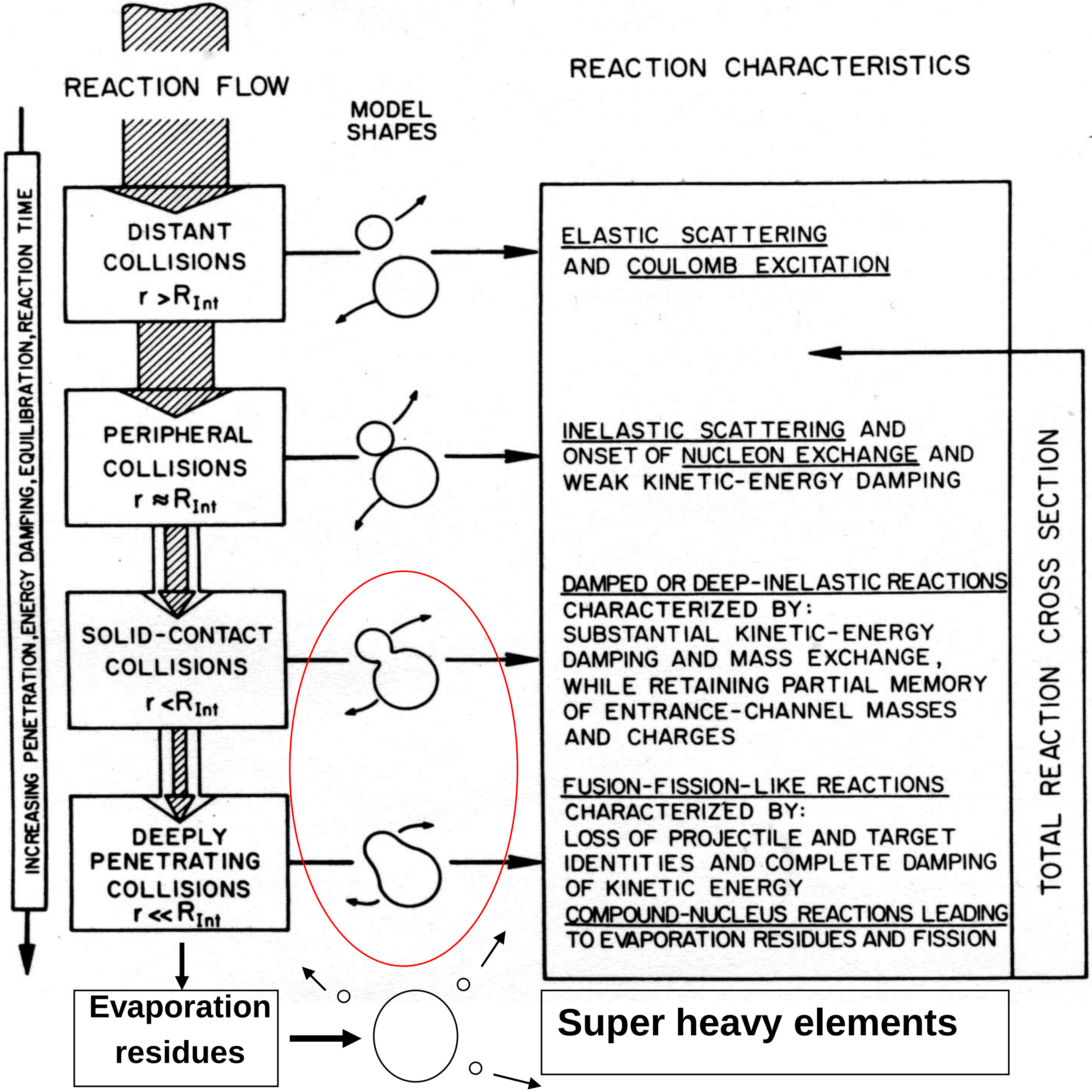
Introduction

The experimental knowledge on fusion between light and medium-heavy nuclei at sub- and near-barrier energies has grown considerably in the last twenty years

1.M. Dasgupta, D.J. Hinde, N. Rowley, A.M. Stefanini,Annu. Rev. Nucl. Part. Sci. 48, 401 (1998).

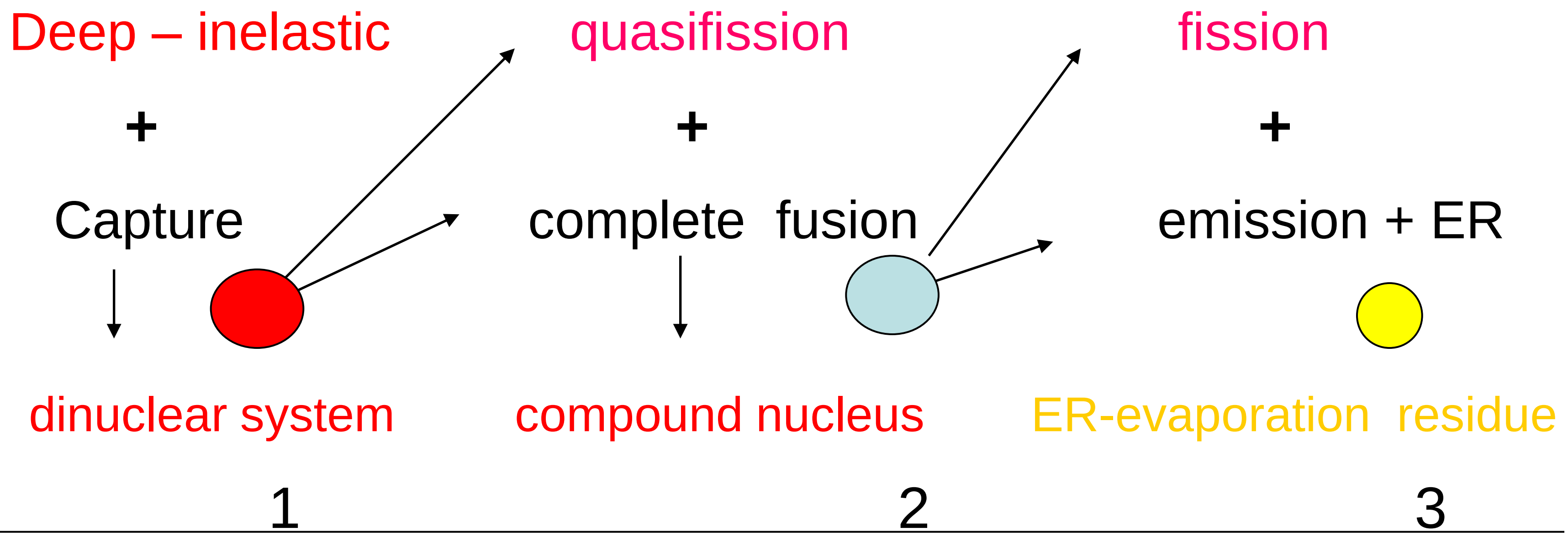
2. A.B. Balantekin, N. Takigawa, Rev. Mod. Phys. 70, 77 (1998)..

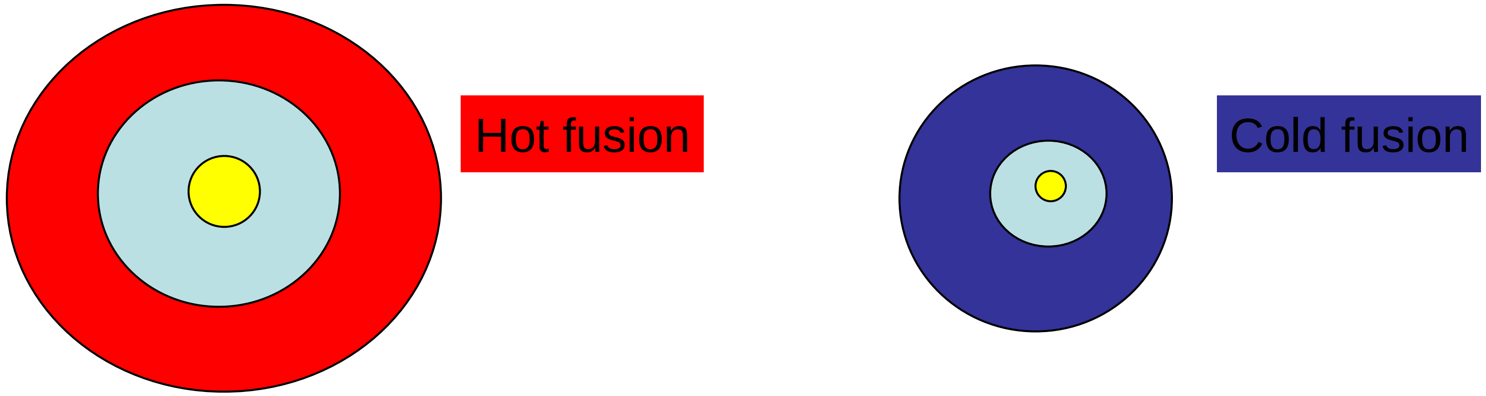
The theoretical models are able to reproduce and predict the main features of such processes, but properly understanding the fusion dynamics for heavy systems requires many more ingredients. The need for more experimental data to disentangle various concurrent effects, is clearly felt. A full understanding of all steps of the reaction dynamics is very important for the challenging issue of superheavy elements production and new isotopes far from the valley of stability.


REACTION FLOW
MODEL SHAPES
REACTION CHARACTERISTICS
INCREASING PENETRATION, ENERGY DAMPING, EQUILIBRATION, REACTION TIME
DISTANT COLLISIONS
r > R_Int
ELASTIC SCATTERING AND COULOMB EXCITATION
PERIPHERAL COLLISIONS
r ≈ R_Int
INELASTIC SCATTERING AND ONSET OF NUCLEON EXCHANGE AND WEAK KINETIC-ENERGY DAMPING
SOLID-CONTACT COLLISIONS
r < R_Int
DAMPED OR DEEP-INELASTIC REACTIONS
CHARACTERIZED BY:
SUBSTANTIAL KINETIC-ENERGY DAMPING AND MASS EXCHANGE, WHILE RETAINING PARTIAL MEMORY OF ENTRANCE-CHANNEL MASSES AND CHARGES
DEEPLY PENETRATING COLLISIONS
r << R_Int
FUSION-FISSION-LIKE REACTIONS
CHARACTERIZED BY:
LOSS OF PROJECTILE AND TARGET IDENTITIES AND COMPLETE DAMPING OF KINETIC ENERGY
COMPOUND-NUCLEUS REACTIONS LEADING TO EVAPORATION RESIDUES AND FISSION
TOTAL REACTION CROSS SECTION
Evaporation residues
Super heavy elements

Description of the nucleus-nucleus collision at energies < 10A MeV as the 3 stage process.

$$\sigma_{ER}(E_{Lab},L) = \langle \sigma_{cap}(E_{Lab},L;\{\alpha_l\})\, P_{CN}(E_{Lab},L;\{\alpha_l\})\, W_{surv}(E_{Lab},L;\{\alpha_l\}) \rangle_{\{\alpha\}}$$

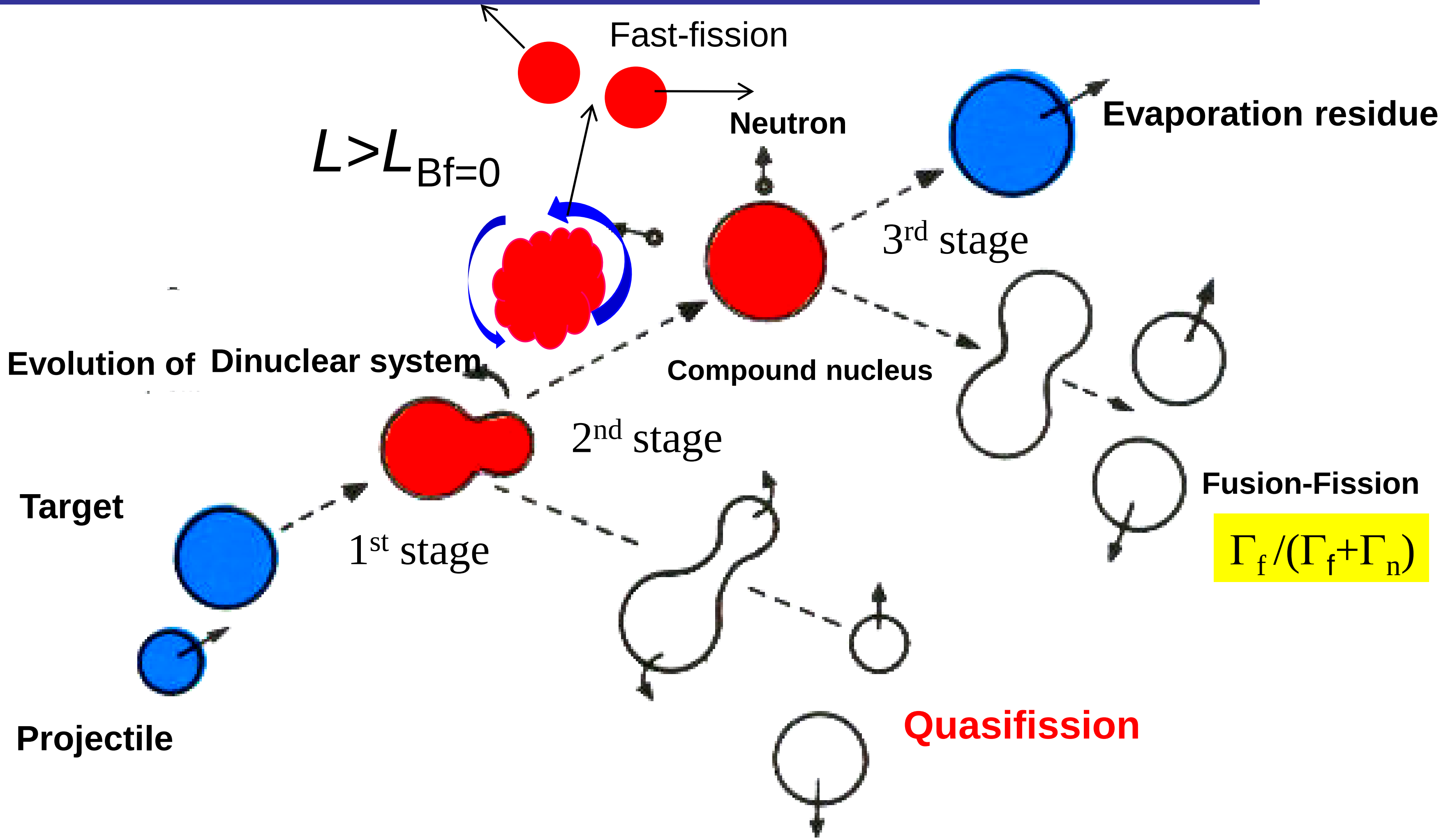




The formation of dinuclear systems

- Dinuclear system is formed due to shell effects as the quantum states of the neutron and proton systems of nuclei.
- Shell effects is observed as cluster states in the large amplitude collective motions of nuclei.
- The observed cluster emission, mass-charge distribution of the quasifission fragments and spontaneous asymmetric fission of Th, U and Cf isotopes proved the strong role of shell structure.
- Reactions of heavy ion collisions and fission (spontaneous and induced) processes can be studied well using dinuclear system concept.

Three final stages of Competition between complete fusion and quasifission



Capture=Quasifission + Fast-fission + Fusion-Fission + Evaporation residues

re

About description of the events of the synthesis of superheavy elements

The measured evaporation cross section can be described by the formula:

$$\sigma_{ER}(E^*) = \sum_{\ell=0}^{\ell=\ell_f} \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell)\, P_{\text{CN}}(E^*, \ell) W_{\text{surv}}\,(E^*, \ell)$$

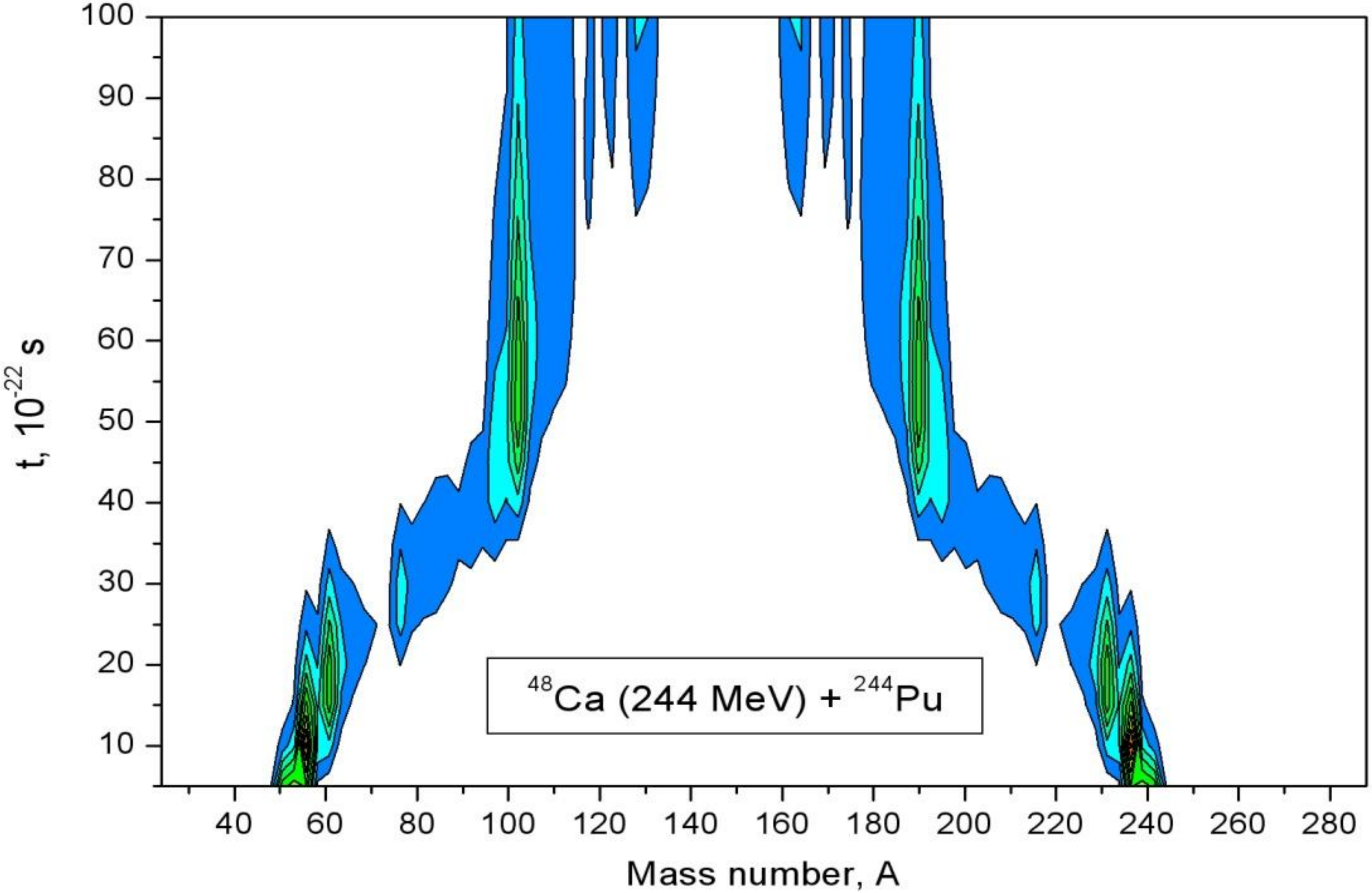
where

$$\sigma_{\text{fus}}(E_{\text{c.m.}}, \ell) = \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell)\, P_{\text{CN}}(E^*, \ell)$$

is considered as the cross section of compound nucleus formation; W_{surv} is the survival probability of the heated and rotating nucleus. The smallness of P_{CN} means hindrance to fusion caused by huge contribution of quasifission process:

$$\sigma_{\text{qfis}}(E_{\text{c.m.}}, \ell) = \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell)\,(1 - P_{\text{CN}}(E^*, \ell))$$

Evolution of mass distributions of the dinuclear system fragments $Y_z(t)$



Calculation of the competition between complete fusion and quasifission: $P_{cn}(E_{DNS},L)$

$$P_{CN}(E^*_{DNS},\ell)=\sum_{Z_{sym}}^{Z_{max}} Y_Z(E^*_{DNS},\ell)P^{(Z)}_{CN}(E^*_{DNS},\ell)$$

where

$$P^{(Z)}_{CN}(E^*_{DNS},\ell)=\frac{\rho(E^*_{DNS}(Z)-B^*_{fus}(Z),\ell)}{\rho(E^*_{DNS}(Z)-B^*_{fus}(Z),\ell)+\rho(E^*_{DNS}(Z)-B^*_{qf}(Z),\ell)+\rho(E^*_{DNS}(Z)-B^*_{sym}(Z),\ell)}$$

$$\frac{\partial}{dt}Y_Z(E^*_Z,\ell,t)=\Delta^{(-)}_{Z+1}Y_{Z+1}(E^*_Z,\ell,t)+\Delta^{(+)}_{Z-1}Y_{Z-1}(E^*_Z,\ell,t)$$
$$-(\Delta^{(-)}_Z+\Delta^{(+)}_Z+\Lambda^{\rm qf}_Z)Y_Z(E^*_Z,\ell,t)\,,\quad \text{for}\quad Z=2,3,\ldots,Z_{\rm tot}-2\,. \qquad (6)$$

Here, the transition coefficients of multinucleon transfer are calculated as in Ref. 18

$$\Delta^{(\pm)}_Z=\frac{1}{\Delta t}\sum_{P,T}|g^{(Z)}_{PT}|^2 n^{(Z)}_{T,P}(t)(1-n^{(Z)}_{P,T}(t))\frac{\sin^2(\Delta t(\tilde\varepsilon_{P_Z}-\tilde\varepsilon_{T_Z})/2\hbar)}{(\tilde\varepsilon_{P_Z}-\tilde\varepsilon_{T_Z})^2/4}\,, \qquad (7)$$

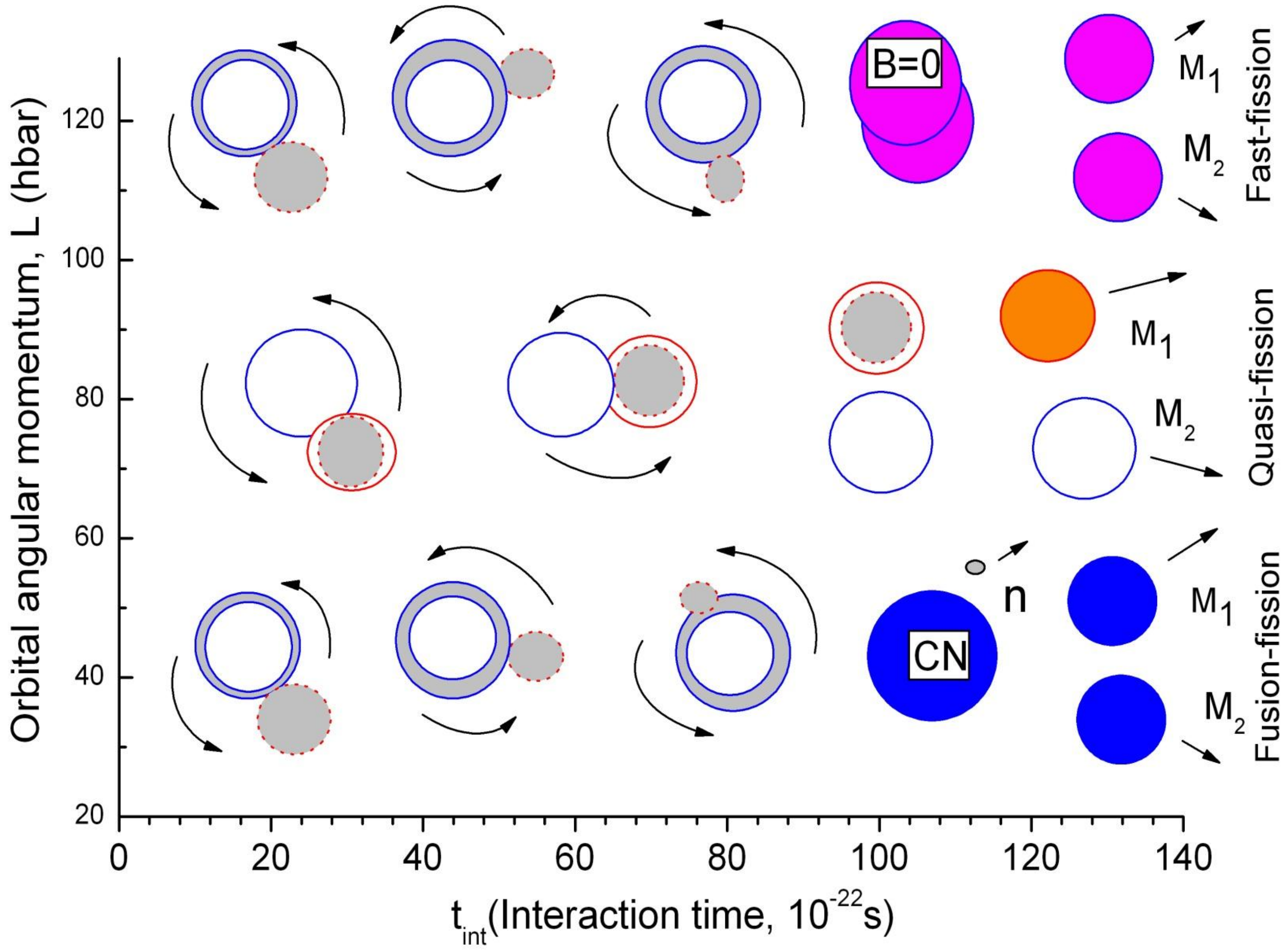
Fazio G. et al, Modern Phys. Lett. A 20 (2005) p.391

What we know about quasifission fragments?

- The mass distribution its fragments has a maximum usually near magic numbers Z=20, 28, 50, 82 and N=20, 28, 50, 82;
- Total kinetic energy distribution is very close to Viola systematics as for fusion-fission: $TKE=Z_1 Z_2 e^2/D(A_1,A_2)$;
- Angular distribution of fragments has more large anisotropy in comparison with that of fusion-fission.

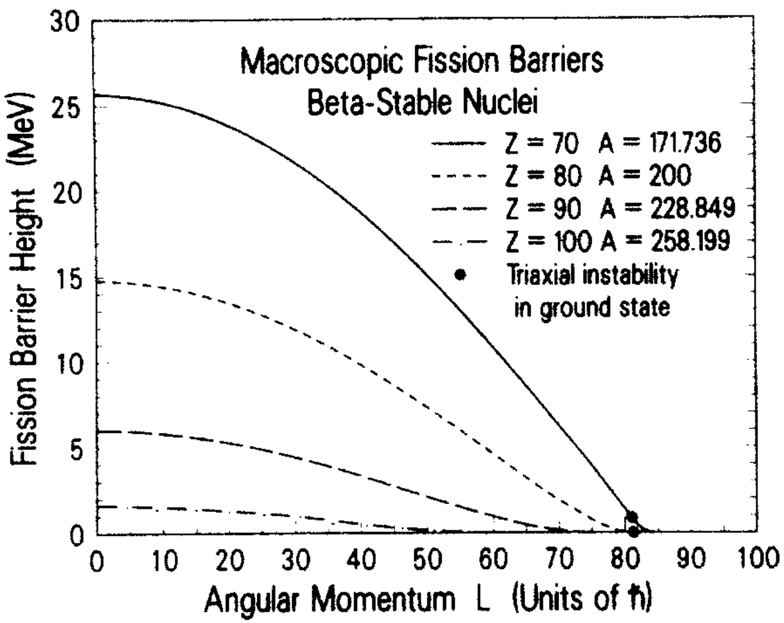
We would like to stress that angular distribution of quasifission fragments is mainly anisotropic but it may be isotropic and angular distribution of fusion-fission fragments may be isotropic in dependence on the reaction dynamics.

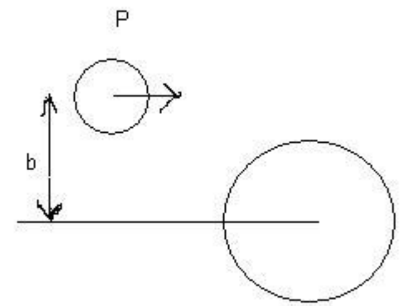
Mechanisms of the reaction following after capture: Fusion-fission, quasifission and fast-fission.



Fast-fission of the mononucleus

33 MACROSCOPIC MODEL (



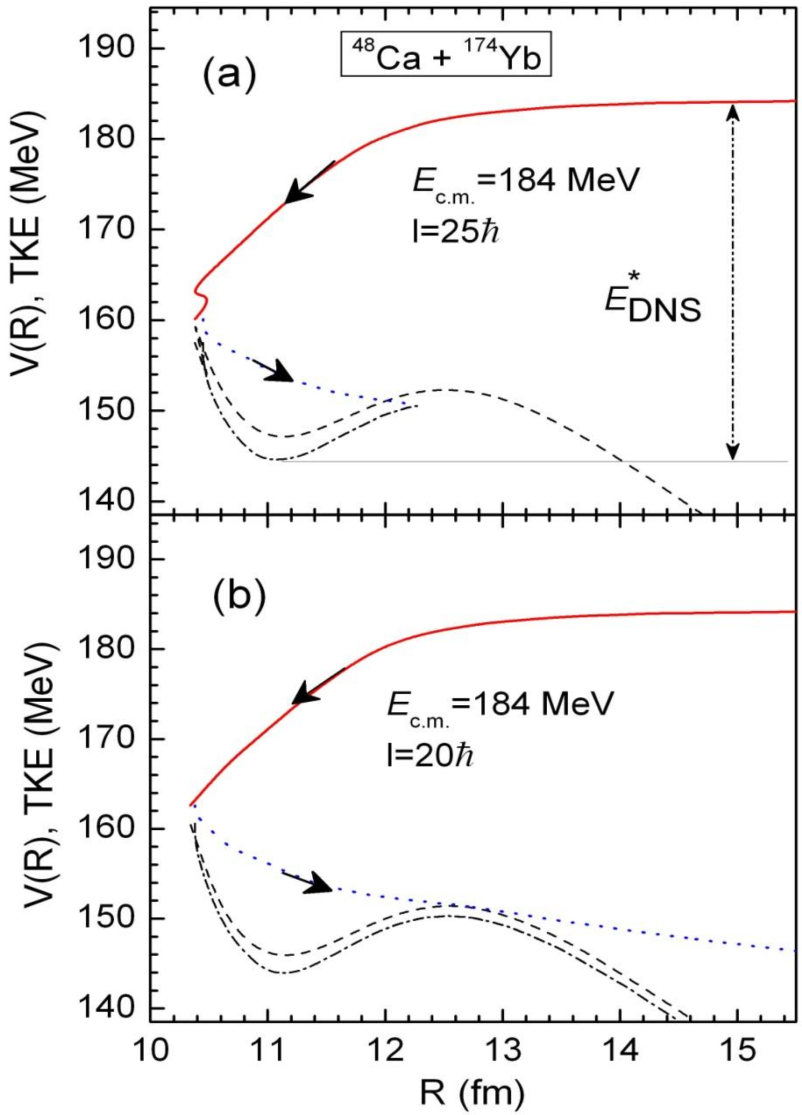


$L_{fus} > L > L_{fis.bar}$

FIG. 10. Same as Fig. 9 for $Z=70$ to 100. There are no solid points for $Z=90$ and $Z=100$ since no triaxial ground states exist for these nuclei.

A.J. Sierk, Phys.Rev. C, **33** (1986) 2039

Difference between classical paths of the capture and deep inelastic collisions



TKE-total kinetic energy

V(R) – nucleus-nucleus potential

E^*_{DNS} – excitation energy of double nuclear system

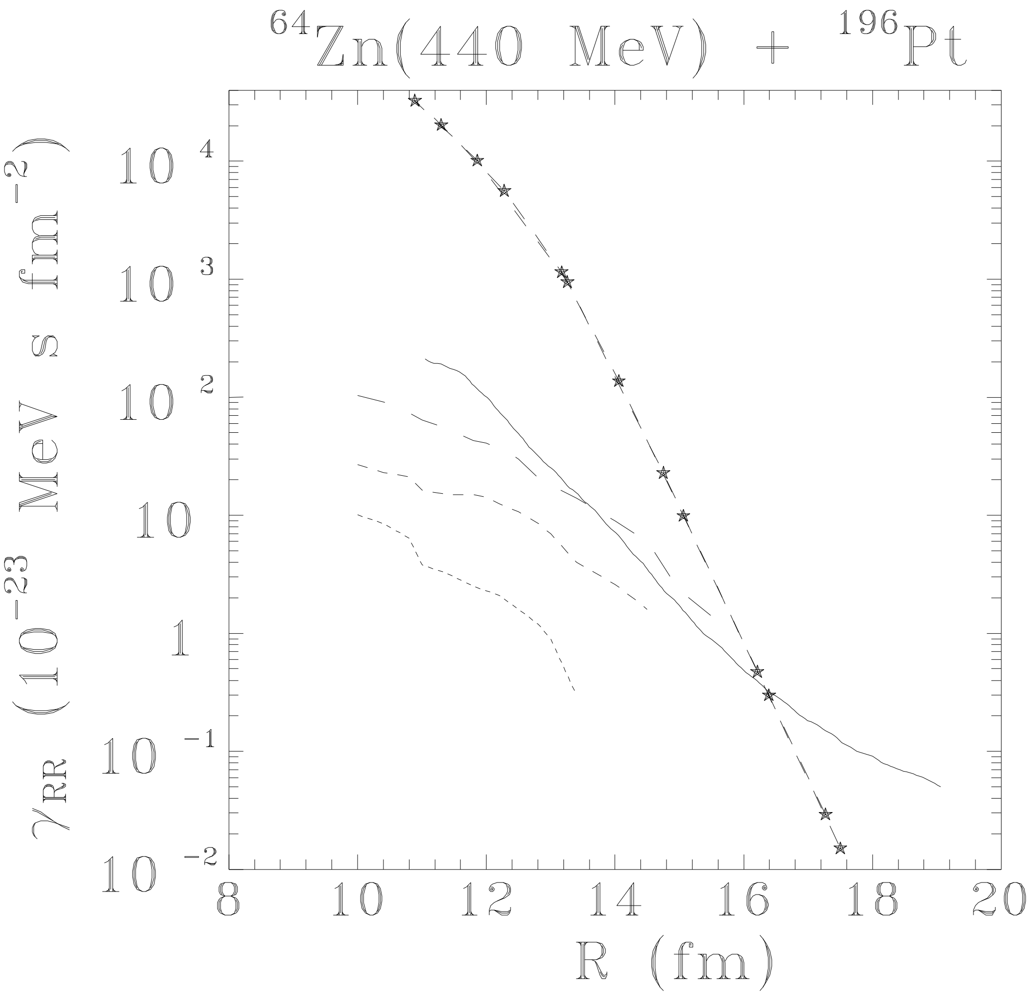
Full momentum transfer reactions

Capture=Fusion+Quasifission +Fast fission

Fusion=Fission+Evaporation residues

Fission >> Evaporation residues

Comparison of the friction coefficients, calculated by different methods



★ D. H. E. Gross and H. Kalinowski, Phys. Rep. **45**, (1978) 175.

Solid line – G.G. Adamian, et al. PRC56 (1997) 373

By Yamaji et al(microscopic):

Long dashed -- Temperatura= 2 MeV

Short dashed- - Temperatura= 1 MeV

Dotted - Temperatura= 0.5 MeV

S. Yamaji and A. Iwamoto,
Z. Phys. A **313**, (1983) 161.

Equations of motion used to find capture of projectile by target

$$\mu(R)\ddot{R} + \gamma_R(R)\dot{R}(t) = -\frac{\partial V(R)}{\partial R} - \dot{R}^2 \frac{\partial \mu(R)}{\partial R}$$

$$\mu(R) = \delta\mu(R) + m_0 A_{\mathrm{T}} A_{\mathrm{P}}/A_{\mathrm{tot}}$$
$$\times \left(1 - \frac{2}{A_{\mathrm{tot}}} \int \frac{\rho_1^{(0)}(\mathbf{r}-\mathbf{r_1})\rho_2^{(0)}(\mathbf{r}-\mathbf{r_2})}{\rho_1^{(0)}(\mathbf{r}-\mathbf{r_1}) + \rho_2^{(0)}(\mathbf{r}-\mathbf{r_2})} \mathrm{d}^3\mathbf{r}\right),$$

$$\frac{dL}{dt} = \gamma_\theta(R)R(t)\left[\dot{\theta}R(t) - \dot{\theta}_1 R_{1eff} - \dot{\theta}_2 R_{2eff}\right]$$

$$L_0 = J_R\dot{\theta} + J_1\dot{\theta}_1 + J_2\dot{\theta}_2 \,, \qquad E_{rot} = \frac{J_R\theta^2}{2} + \frac{J_1\theta_1{}^2}{2} + \frac{J_2\theta_2{}^2}{2}$$

Nucleus-nucleus interaction potential

$$V_C(R,\alpha_1,\alpha_2) = \frac{Z_1 Z_2}{R} e^2$$

$$+ \frac{Z_1 Z_2}{R^3} e^2 \left\{ \left(\frac{9}{20\pi} \right)^{1/2} \sum_{i=1}^{2} R_{0i}^2 \beta_2^{(i)} P_2(\cos\alpha_i) + \frac{3}{7\pi} \sum_{i=1}^{2} R_{0i}^2 \left[\beta_2^{(i)} P_2(\cos\alpha_i) \right]^2 \right\}$$

$$V_{nucl}(R,\alpha_1,\alpha_2) = \int \rho_1^{(0)}(\vec{r} - \vec{R}) f_{eff} \left[\rho_1^{(0)} + \rho_2^{(0)} \right] \rho_2^{(0)}(\vec{r}) d^3\vec{r}$$

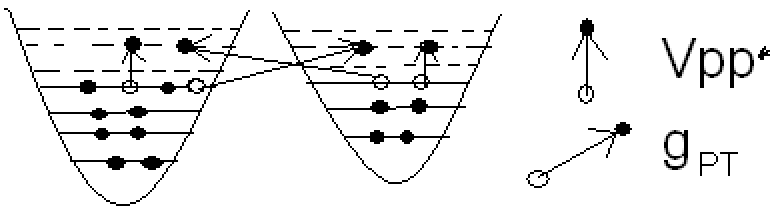
$$\rho_i^{(0)}(\vec{r}, \vec{R}_i, \alpha_i, \theta_i, \beta_2{}^{(i)}) = \left\{ 1 + \exp\left[\frac{\left| \vec{r} - \vec{R}_i(t) \right| - R_{oi}(1 + \beta_2^{(i)} Y_{20}(\theta_i, \alpha_i))}{a} \right] \right\}^{-1}.$$

$$V_{rot} = \hbar^2 \frac{l(l+1)}{2\mu[R(\alpha_1, \alpha_2)]^2 + J_1 + J_2}$$

Friction coefficients

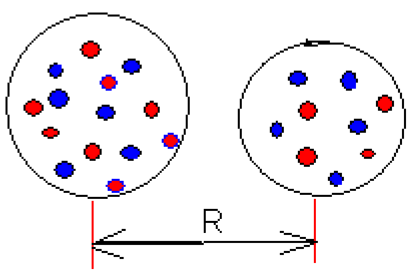
$$\gamma_\lambda = \frac{2}{i\hbar^2 D_\lambda} \sum_{i,i',j,k} \left(n_j^{(i)} - n_k^{(i')}\right) \left| \frac{\partial V_{jk}(R,\beta_\lambda)}{\partial \beta_\lambda} \right|^2 \int_{t_0}^{t} dt' (t-t') \exp\left(\frac{t-t'}{\tau_{jk}}\right) \sin\left[(\varepsilon_j - \varepsilon_k)(t-t')/\hbar\right]$$

$$\frac{1}{\tau_i^{(\alpha\alpha}} = \frac{\sqrt{2}\pi}{32\hbar\varepsilon_{F_K}^{(\alpha\alpha}} \left[(f_K - g)^2 + \frac{1}{2}(f_K + g)^2 \right] \left[(\pi\pi_K)^2 + (\varepsilon_i - \lambda_K^{(\alpha\alpha})^2 \right] \left[1 + \exp\left(\frac{\lambda_K^{(\alpha\alpha} - \varepsilon_i}{T_K} \right) \right]^{-1}$$



ε_j and ε_k are single particle energies of nucleons in dinuclear syste,;

$$\Gamma_j = \hbar / \tau_j$$



Decay width of the single-particle excitations of nucleons caused by residual forces .

G.G. Adamian, et al. Phys. Rev. C**56** No.2, (1997) p.373-380

Hamiltonian for calculation of the transport coefficients

The macroscopic motion of nucleus and microscopic motion of nucleons must be calculated simultaneously.

$$\mathrm{H} = \mathrm{H}_{\mathrm{coll}} + \mathrm{H}_{\mathrm{micr}} + \delta \mathrm{V} \qquad (1)$$

where

$$\mathrm{H}_{\mathrm{coll}} = \frac{\mathrm{P}^2}{2\mu} + \mathrm{U}(\mathrm{R}) \text{ - for the relative motion of nuclei;} \qquad (2)$$

$$\mathrm{H}_{\mathrm{micr}} = \sum_{i_P} \varepsilon_{i_P} \hat{a}^+_{i_P} \hat{a}_{i_P} + \sum_{i_T} \varepsilon_{i_T} \hat{a}^+_{i_T} \hat{a}_{i_T} - \textit{for nucleons of nuclei}; \qquad (3)$$

$$\delta \mathrm{V} = \sum_{i_P, j_T} g_{i_P j_T}(R)(\hat{a}^+_{i_P} \hat{a}_{j_T} + \hat{a}^+_{j_T} \hat{a}_{i_P}) + \sum_{i_P, j_T} \kappa_{i_P j_T}(R)(\hat{a}^+_{i_P} \hat{a}_{j_T} + \hat{a}^+_{j_T} \hat{a}_{i_P})$$

$$+ \sum_{i_P, j_P} \Lambda^{(T)}_{i_P j_P}(R) \hat{a}^+_{i_p} \hat{a}_{j_p} + \sum_{i_P, j_P} \Lambda^{(P)}_{i_T j_T}(R) \hat{a}^+_{i_T} \hat{a}_{j_T} \text{ -- nucleon exchange between nuclei and}$$

$$\text{particle – hole excitations in nuclei;} \qquad (4)$$

$g_{i_P j_T}$, $\kappa_{i_P j_T}$ and $\Lambda^{(P)}{}_{i_T j_T}$ – matrix elements of nucleon exchange between nuclei and particle – hole excitations in them caused by meanfield of partner nucleus.

Master equations for the nucleon occupation numbers and Equation of motion for the relative distance

$$i\hbar \frac{\partial \hat{n}(t)}{\partial t} = [H(R(t),\hat{n}(t))], \qquad (5)$$

$$n_i(t) = a_i^+ a_i \qquad i=P,T$$

$$i\hbar \frac{\partial \hat{P}(t)}{\partial t} = [H(R(t),\hat{P}(t))], \qquad (6)$$

$$P \equiv (n_P, j_P, l_P, m_P)$$

$$T \equiv (n_T, j_T, l_T, m_T)$$

$$i\hbar \frac{\partial \tilde{n}_i(t)}{\partial t} = [H, n_i(t)] - \frac{i\hbar}{\tau_i}\left[n_i(t) - n_{i\,eq}(R(t))\right]$$

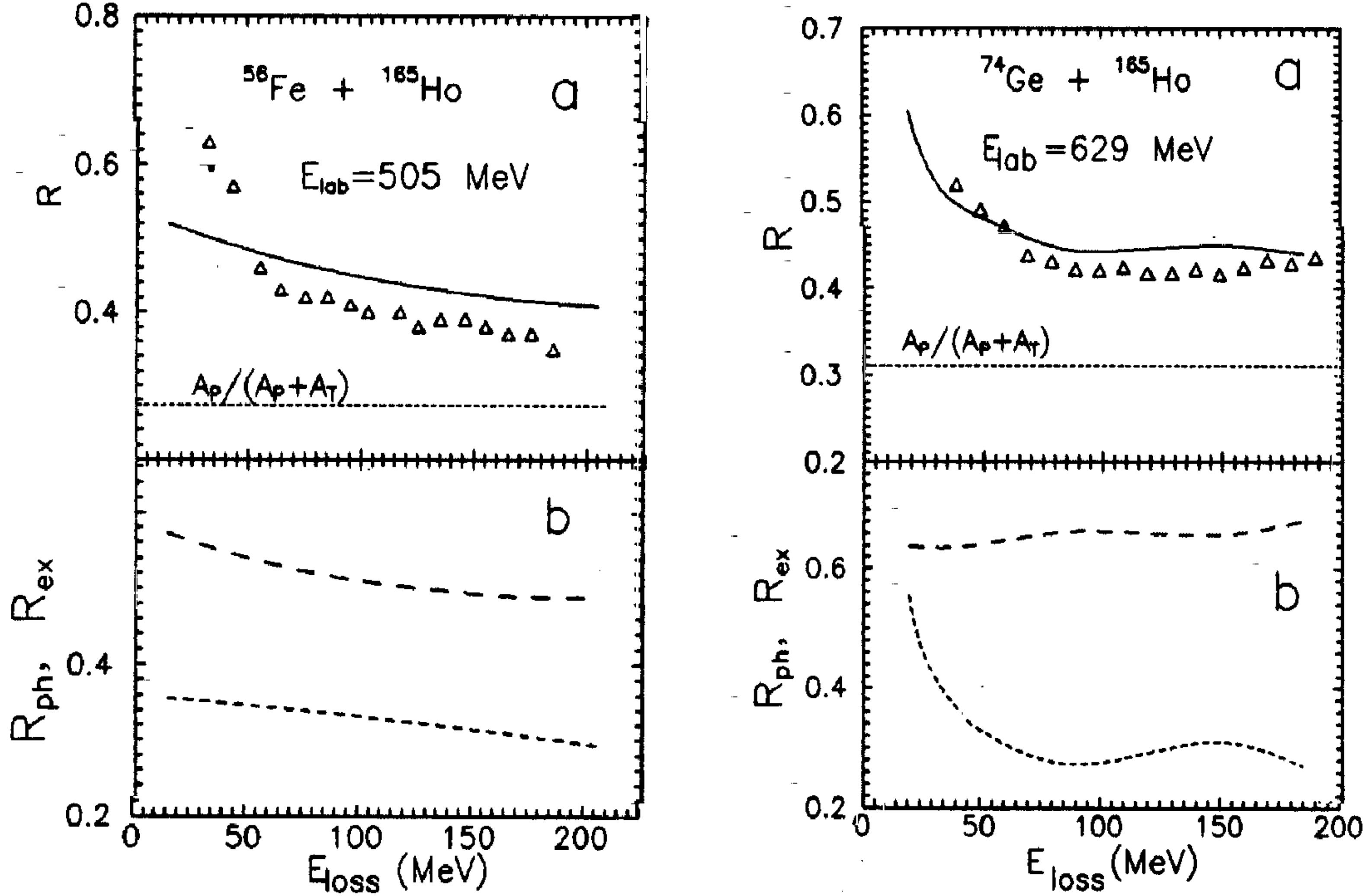
$$\tilde{n}_i = \tilde{n}_i^{eq}(R(t))\left[1 - \exp\left(\frac{-\Delta t}{\tau_i}\right)\right] + n_i(t)\exp\left(\frac{-\Delta t}{\tau_i}\right) \qquad (7)$$

$$n_i(t) = \tilde{n}_i(t-\Delta t) + \sum_k \overline{W}_{ik}(R(t),\Delta t)[\tilde{n}_k(t-\Delta t) - \tilde{n}_i(t-\Delta t)] \qquad (8)$$

$$\overline{W}_{ik}(R(t),\Delta t) = \left|V_{ik}(R(t))\right|^2, V_{ik}(R) = \langle i|V(R)|k\rangle \qquad (9)$$

G.G. Adamian, et al. Phys. Rev. C**53,** (1996) p.871-879
R.V. Jolos et al., Eur. Phys. J. A **8, 115–124 (2000)**

Non-equilibrium sharing of excitation energy in the deep-inelastic collisions is explained by nuclear shell structure.



Adamian G.G., et al. Zeit. fur Physik, A**347**, (1994), p.206-210;

Eur. Phys. J. A 8, 115–124 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Effect of shell structure on energy dissipation in heavy-ion collisions

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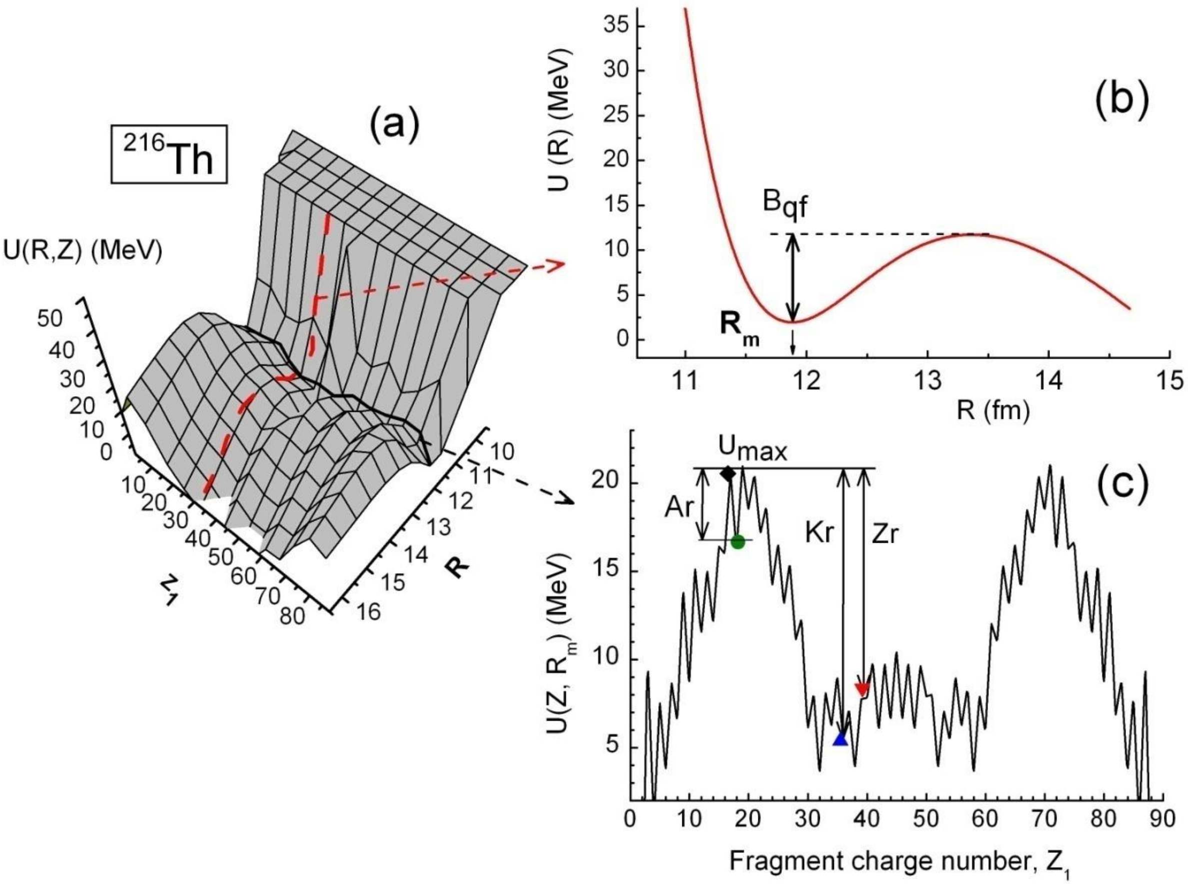
[1] Joint Institute for Nuclear Research, 141980, Dubna, Russia
[2] Heavy Ion Physics Department, Institute of Nuclear Physics, 702132 Ulugbek, Tashkent, Uzbekistan
[3] Institut für Theoretische Physik der Justus-Liebig-Universität, D-35392 Giessen, Germany

$$E^*_{P(T)}(t+\Delta t) = E^*_{P(T)}(t) + \sum_{i_P(j_T)} \left[\tilde{\varepsilon}_{i_P(j_T)}(\mathbf{R}(t)) - \lambda_{P(T)}(\mathbf{R}(t))\right] \times \left[\tilde{n}_{i_P(j_T)}(t+\Delta t) - \tilde{n}_{i_P(j_T)}(t)\right]. \quad (28)$$

Application of the dinuclear system model to the study of synthesis of superheavy elements.

Driving potential $U_{driving}$ (c) for reactions $^{40}Ar+^{172}Hf$, $^{86}Kr+^{130}Xe$, $^{124}Sn+^{92}Zr$ leading to formation of compound nucleus ^{216}Th :

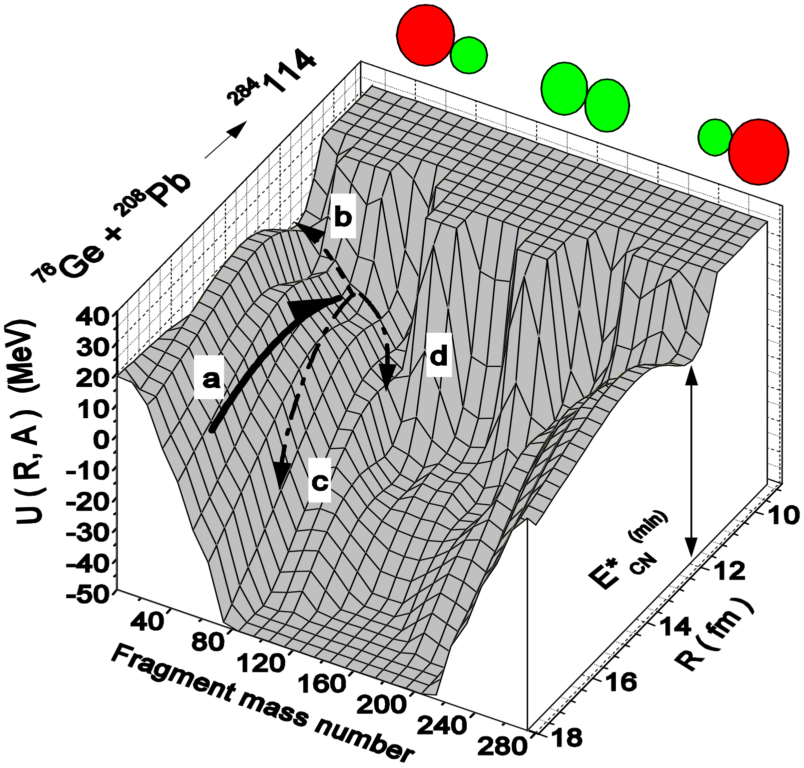


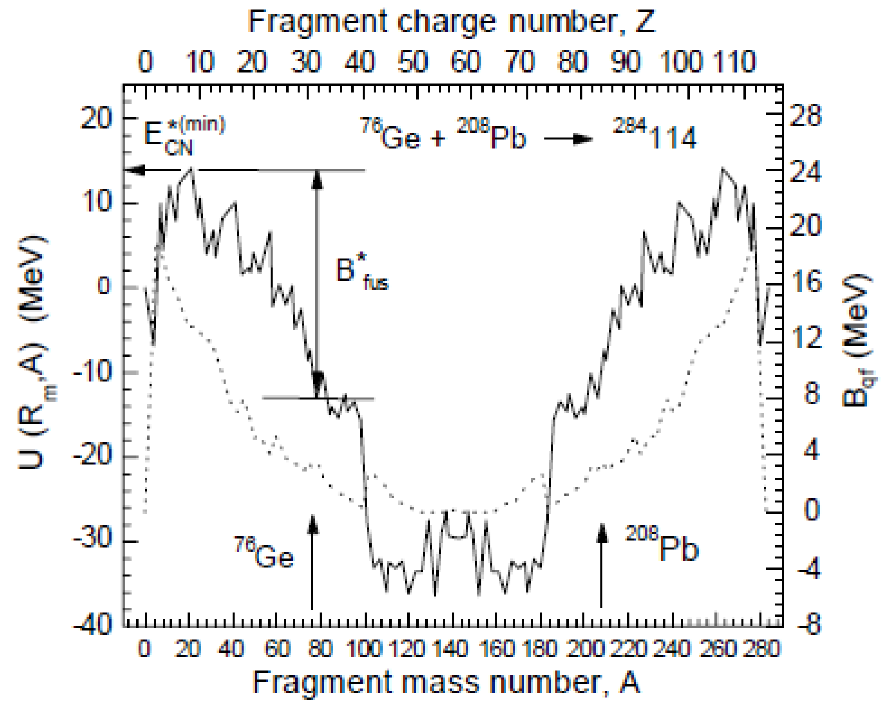
Due to peculiarities of shell structure B_{fus} (Kr) > Bfus (Kr) and, consequently,

σ_{fus} (Kr+Xe) < σ_{fus}(Zr+Sn)

$$U_{driving}=B_1+B_2-B_{(1+2)}+V(R)$$

Potential energy surface of dinuclear system





a- entrance channel;

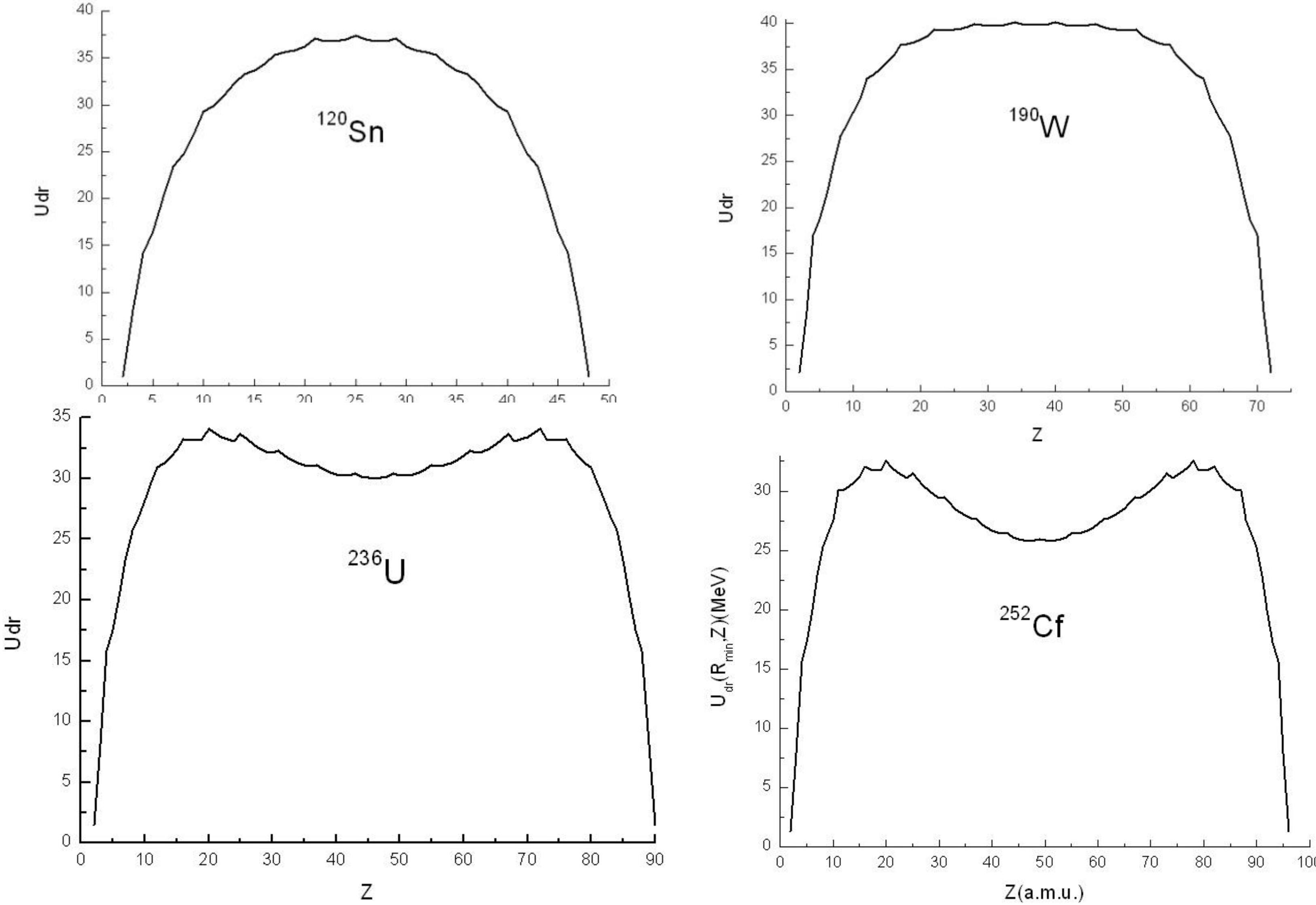
b-fusion channel;

c and **d** are quasifission channels

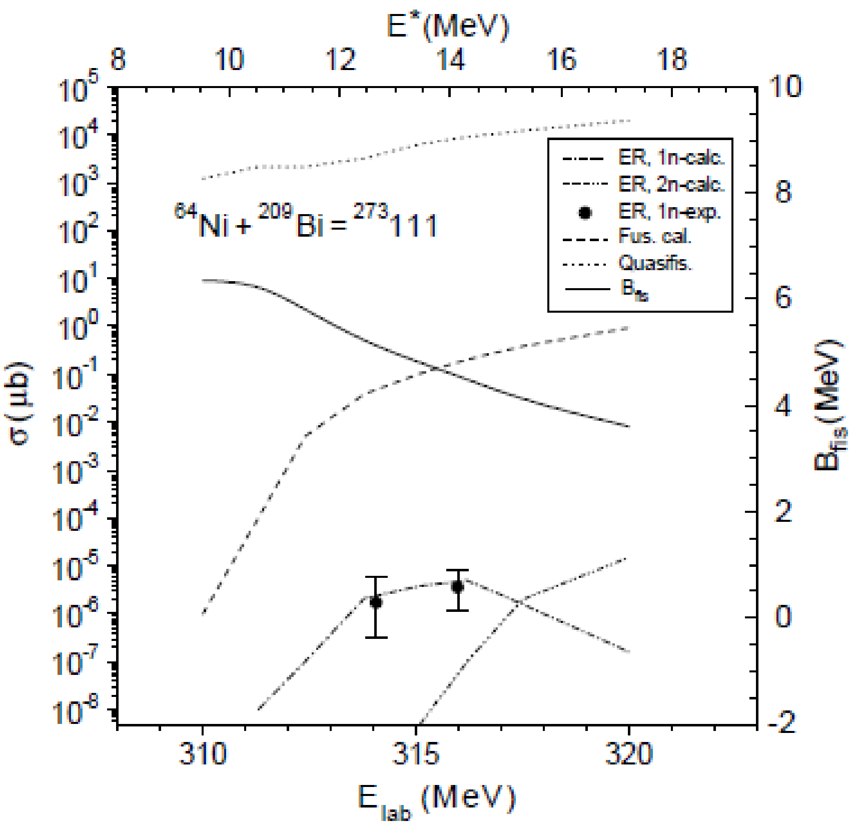
G. Giardina, S. Hofmann, A.I. Muminov, and A.K. Nasirov,
Eur. Phys. J. A **8, 205–216 (2000)**

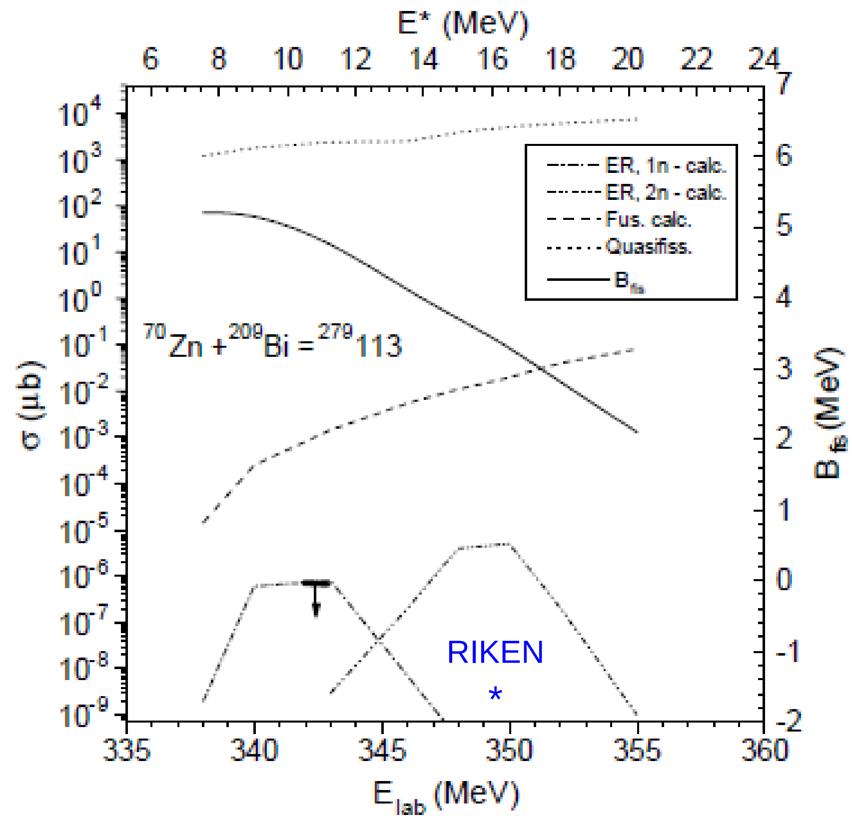
$$U_{dr}\,(A,\, Z,\, ,\, ß_1\, ,\, ß_2\,) = B_1 + B_2 + V\,(A,\, Z,\, ß_1\, ;\, ß_2\, ;\, R) - B_{C\,N} - V_{C\,N}\,(L\,)$$

The change of driving potential by increase of the mass and charge of compound nucleus.



Theoretical results of capture, fusion and evaporation residues cross sections and comparison of them with the experimental data for the "cold" $^{64}Ni+^{209}Bi$ and $^{70}Zn+^{209}Bi$ reactions.





G. Giardina, S. Hofmann, A.I. Muminov, and A.K. Nasirov,
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Results of calculation and comparison of them with the experimental data for the “cold” $^{76}Ge+^{208}Pb$ and $^{70}Zn+^{208}Pb$ reactions.

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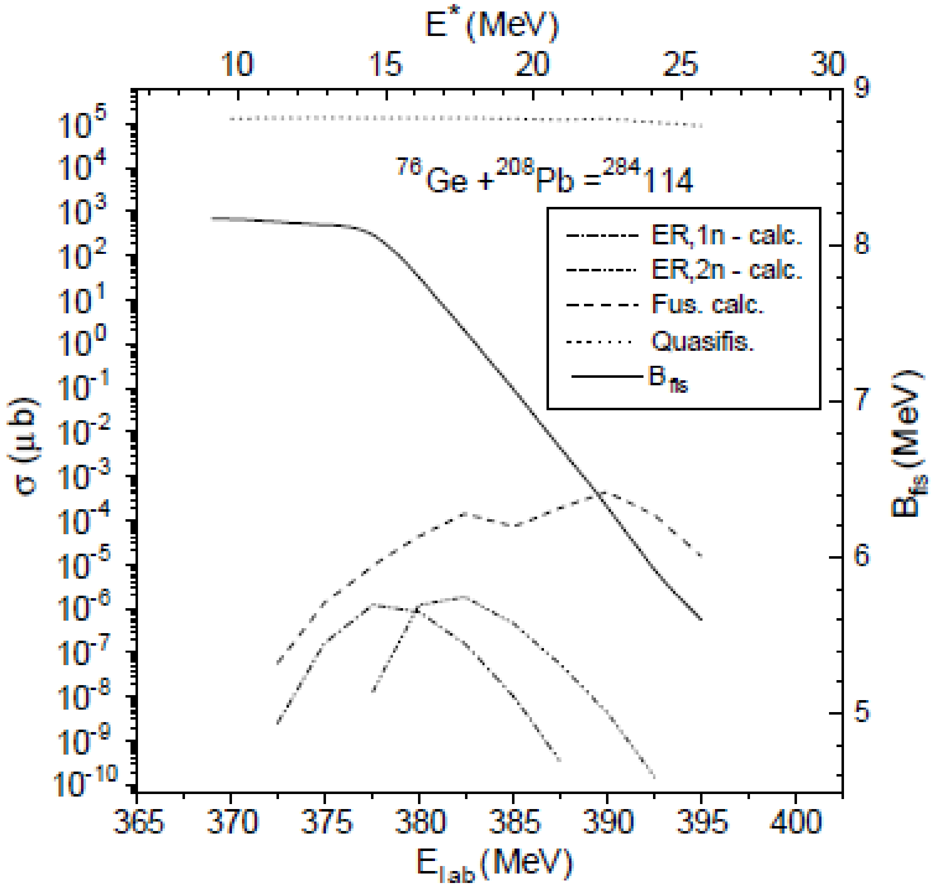
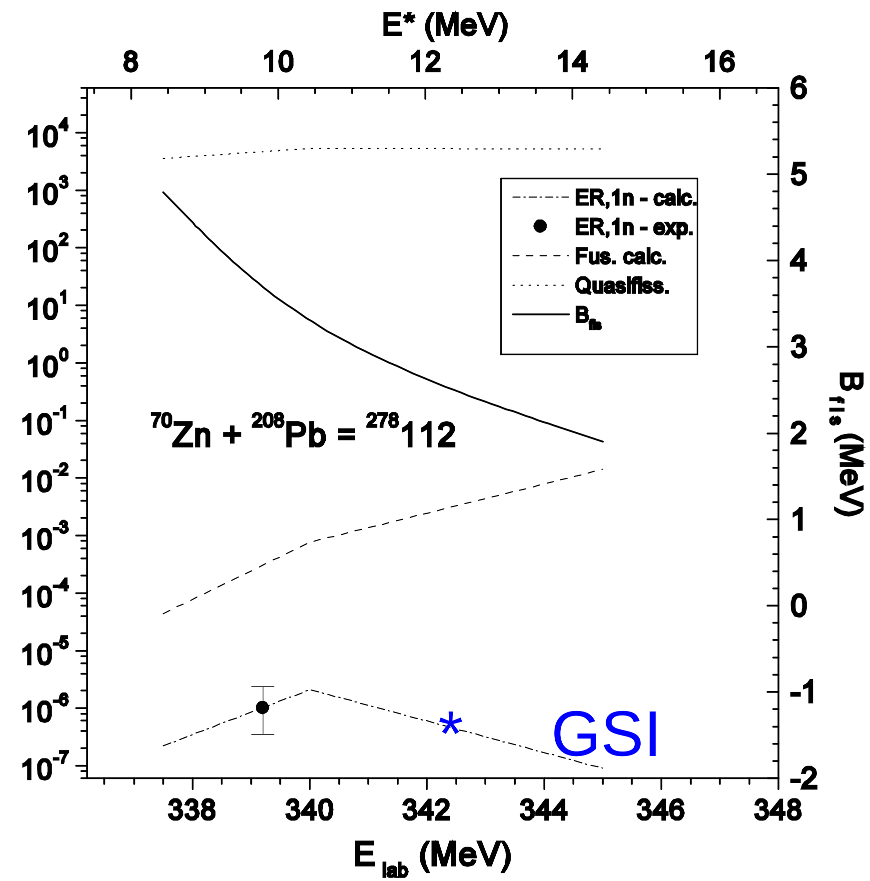
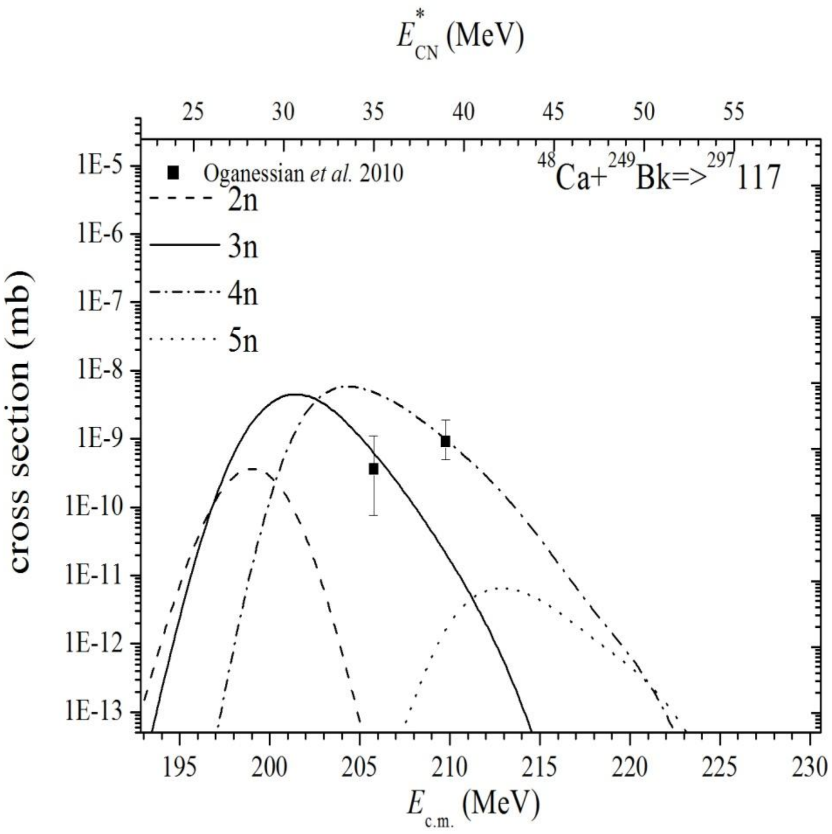
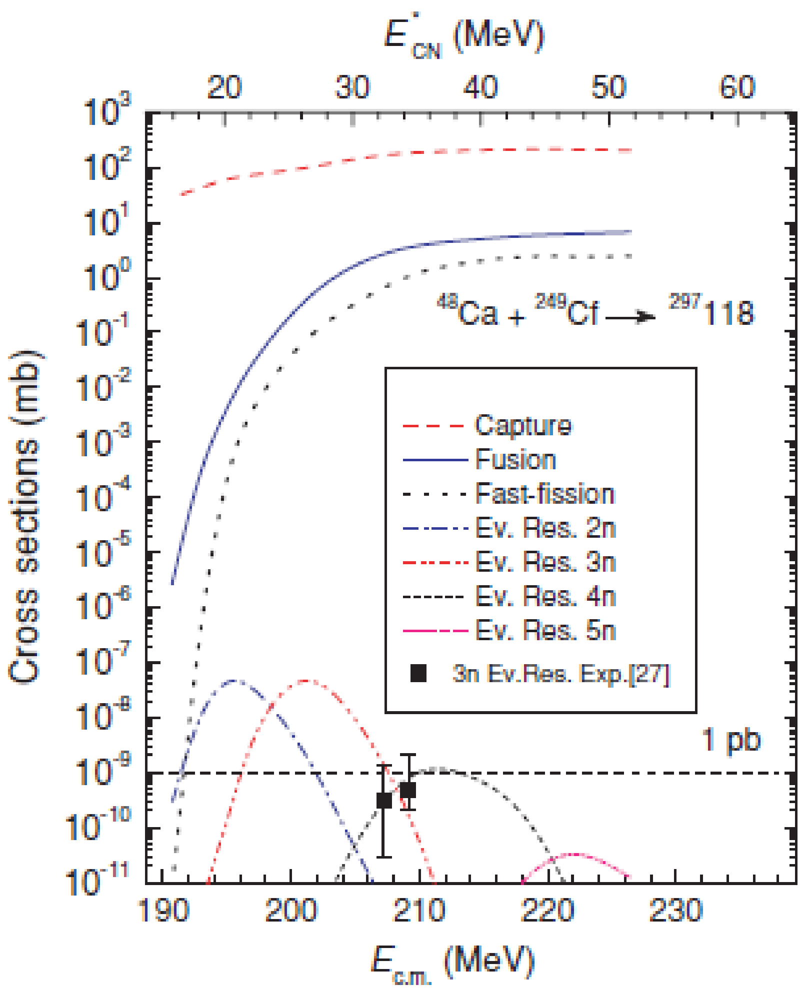


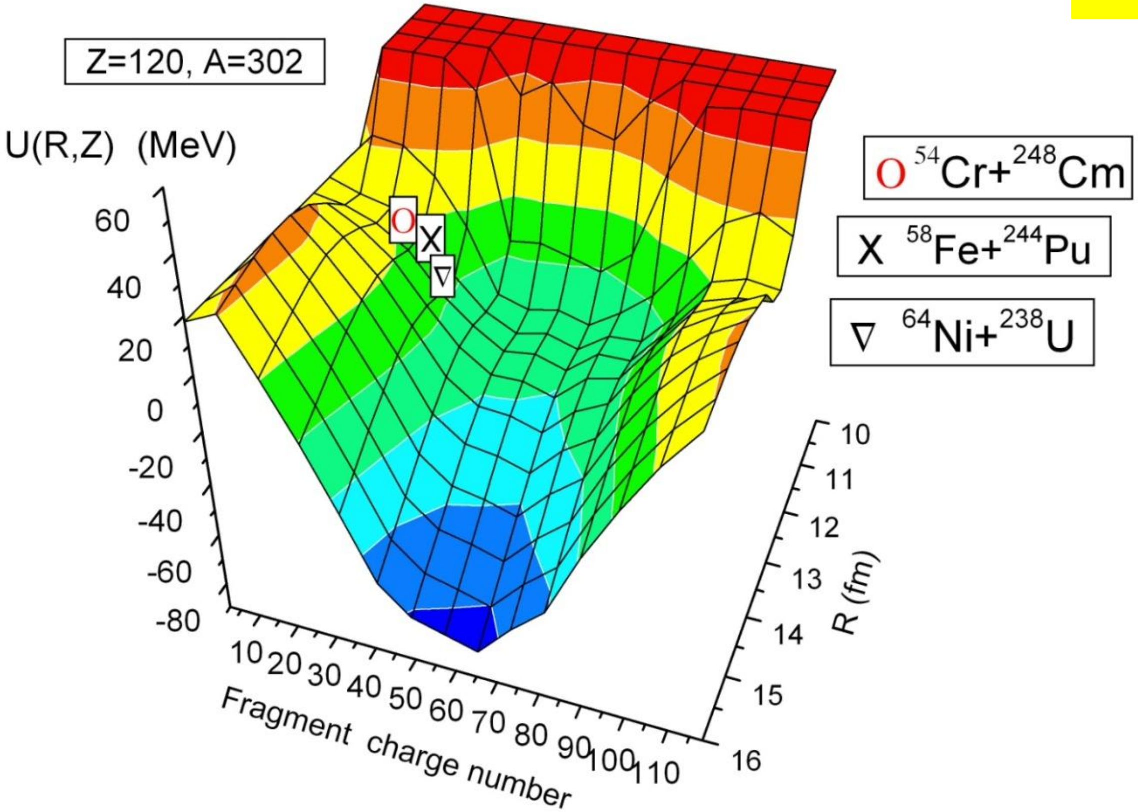


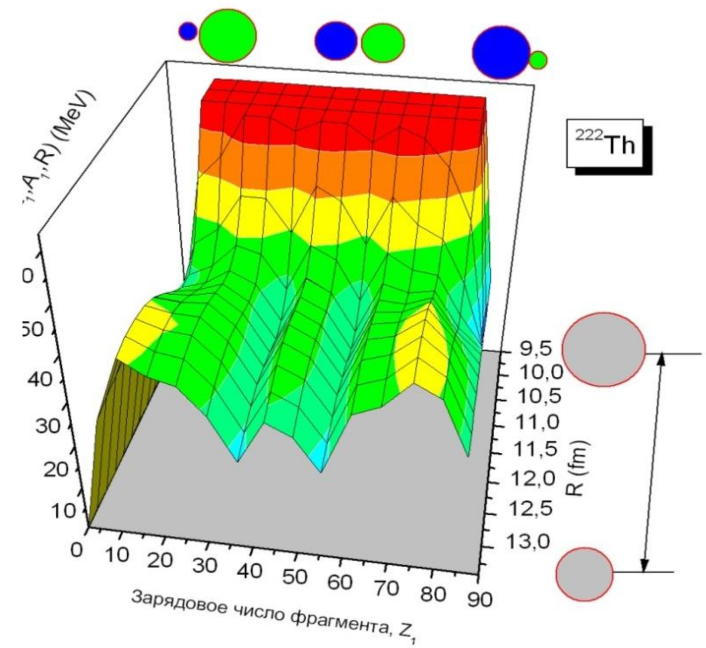
Synthesis of superheavy elements in hot fusion reactions.





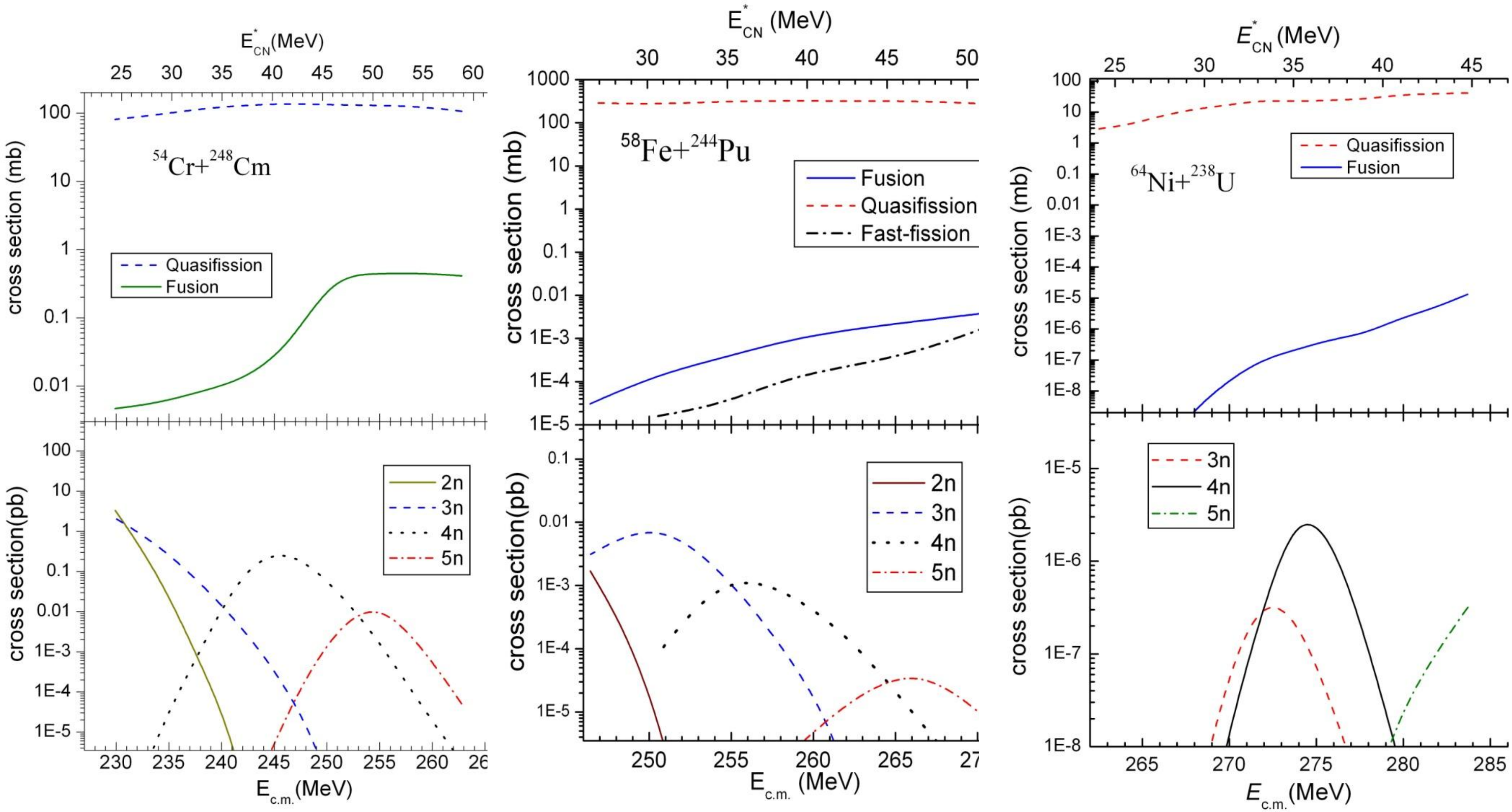
Potential energy surface of dinuclear system





$$U_{dr}\,(A, Z, , \beta_1 , \beta_2) = B_1 + B_2 + V\,(A, Z, \beta_1 ; \beta_2 ; R) - B_{C\,N} - V_{C\,N}\,(L\,)$$

Comparisons of cross sections for complete fusion and formation evaporation residues



Fission barriers calculated by macroscopic-microscopic model:

M. Kowal,P.Jachimowicz,and A. Sobiczewski, Phys. Rev. C **82, 014303 (2010)**

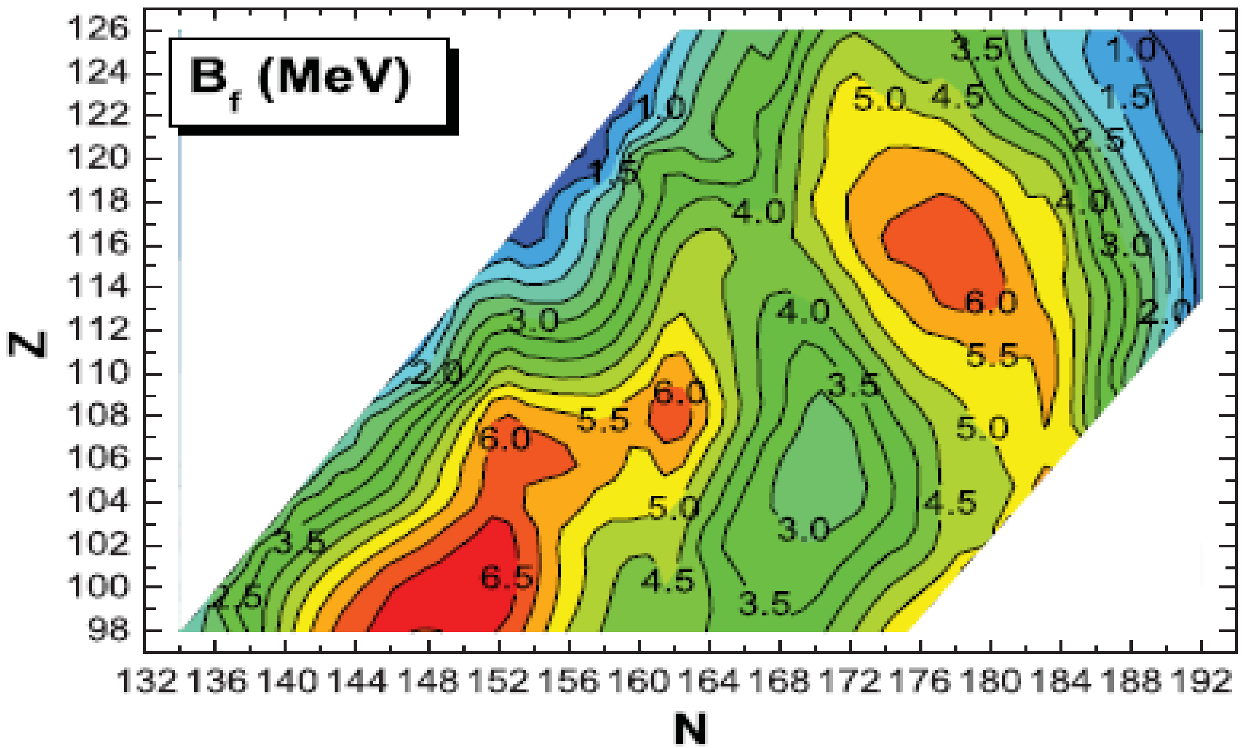


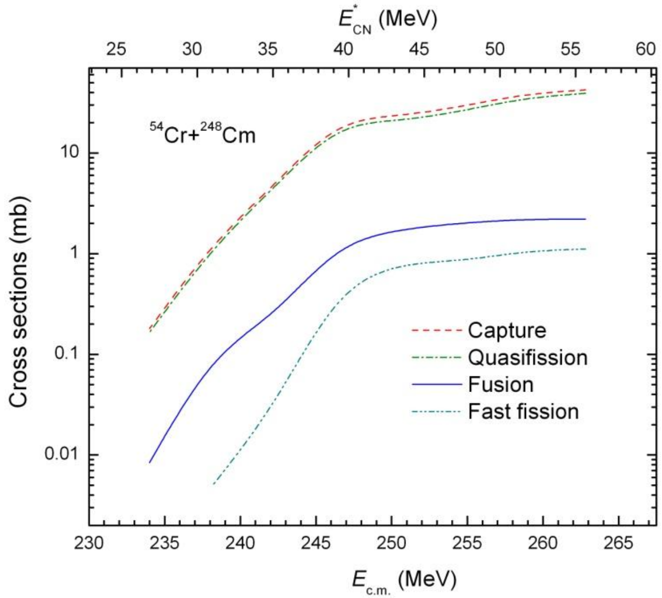
FIG. 6. (Color online) Contour map of calculated fission barrier heights B_f for even-even superheavy nuclei.

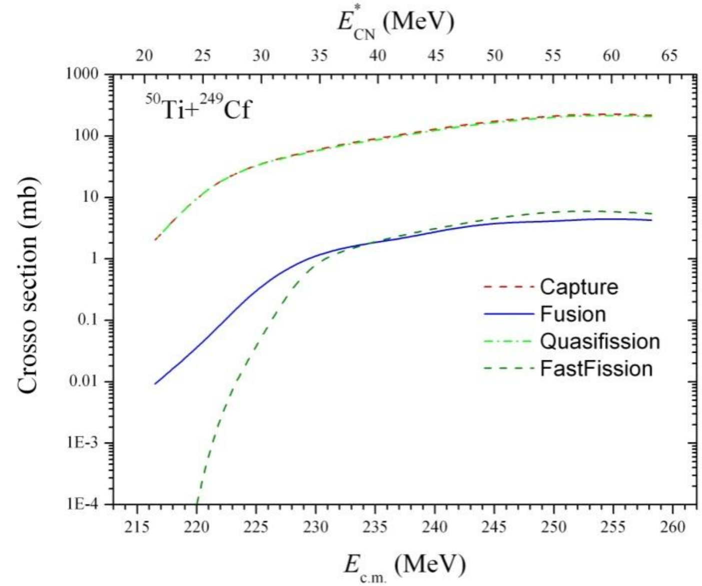
Fission barriers calculated by macroscopic-microscopic model

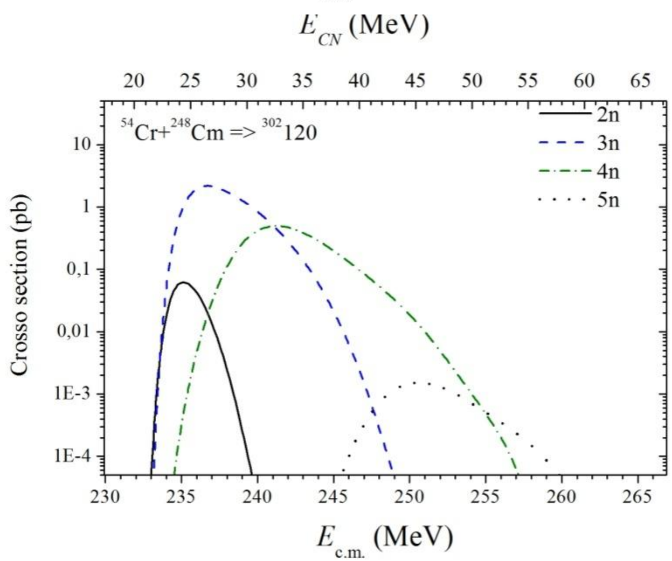
TABLE III. (*Continued.*)

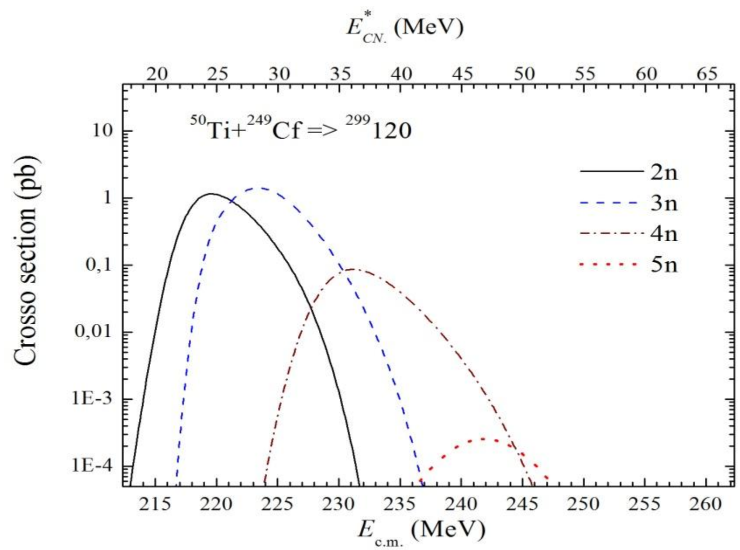
N	A	B_f	N	A	B_f	N	A	B_f	N	A	B_f	N	A	B_f
	$Z = 118$			$Z = 120$			$Z = 122$			$Z = 124$			$Z = 126$	
154	272	0.59	156	276	0.41	158	280	0.80	160	284	0.86	162	288	1.39
156	274	1.36	158	278	0.86	160	282	1.22	162	286	1.81	164	290	2.16
158	276	2.17	160	280	2.92	162	284	2.10	164	288	2.60	166	292	2.85
160	278	2.91	162	282	3.26	164	286	2.92	166	290	3.09	168	294	2.88
162	280	3.78	164	284	2.94	166	288	3.32	168	292	3.28	170	296	3.82
164	282	4.09	166	286	3.16	168	290	3.84	170	294	4.41	172	298	4.43
166	284	3.88	168	288	4.02	170	292	4.72	172	296	4.99	174	300	4.31
168	286	4.05	170	290	4.80	172	294	5.32	174	298	4.71	176	302	4.08
170	288	5.06	172	292	5.33	174	296	5.25	176	300	4.40	178	304	4.01
172	290	5.54	174	294	5.56	176	298	5.03	178	302	4.36	180	306	3.38
174	292	5.86	176	296	5.64	178	300	4.84	180	304	3.72	182	308	2.48
176	294	5.99	178	298	5.50	180	302	4.23	182	306	2.79	184	310	1.70
178	296	6.04	180	300	5.05	182	304	3.74	184	308	2.07	186	312	1.43
180	298	5.72	182	302	4.66	184	306	3.13	186	310	1.43	188	314	0.81
182	300	5.08	184	304	4.20	186	308	1.96	188	312	1.24	190	316	0.29
184	302	4.82	186	306	2.87	188	310	1.42	190	314	0.68	192	318	0.00
186	304	3.51	188	308	1.77	190	312	0.90	192	316	0.14			
188	306	2.43	190	310	1.17	192	314	0.36						
190	308	1.37	192	312	0.75									
192	310	0.56												

Synthesis of superheavy elements in hot fusion reactions.









Dependence of the fission barrier on the excitation energy and angular momentum of compound nucleus.

$$B_{\rm fis}(J,T) = c\ B^{m}_{\rm fis}(J) - h(T)\ q(J)\ \delta W,$$

with

$$h(T) = \begin{cases} 1\,, & T \le 1.65\ \text{MeV}\,, \\ k \exp(-mT)\,, & T > 1.65\ \text{MeV}, \end{cases}$$

and

$$q(J) = \{1 + \exp[(J - J_{1/2})/\Delta J]\}^{-1},$$

where $B^{\rm m}_{\rm fis}(J)$ is the parameterized macroscopic fission barrier [15] depending on angular momentum J, $\delta W = \delta W_{\rm sad} - \delta W_{\rm gs} \simeq -\delta W_{\rm gs}$ is the microscopic (shell) correction to the fission barrier taken from the tables [8] and the constants for the macroscopic fission barrier scaling, temperature and angular momentum dependencies of the microscopic correction are chosen to be as follows: $c = 1.0$, $k = 5.809$, $m = 1.066\ \text{MeV}^{-1}$, $\Delta J = 3\hbar$; for nuclei with $Z > 102$ we use $J_{1/2} = 20\hbar$. This procedure let the shell corrections become dynamical quantities, too.

G.Giardina, et al. Eur. Phys. J. A **8**, 205–216 (2000)

Conclusions

The complete fusion mechanism in the heavy ion collisions strongly depends on the entrance channel peculiarities: mass (charge) asymmetry, shell structure of interacting nuclei, beam energy and angular momentum (impact parameter of collision).

The calculation of the optimal beam energy to reach the maximal cross section of evaporation residues needs the values of fission barrier and binding energy of the being formed compound nucleus.