Evaporation residues cross sections in heavy ion collisions

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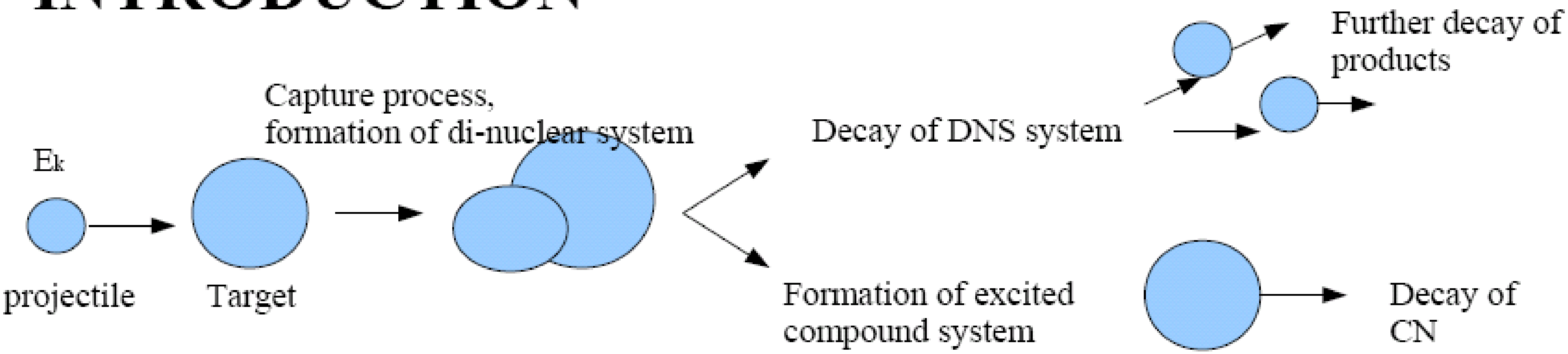
INTRODUCTION



Projectile energy range ~ 1-30 MeV/nucleon,
excitation energy range ~ 40MeV-150MeV

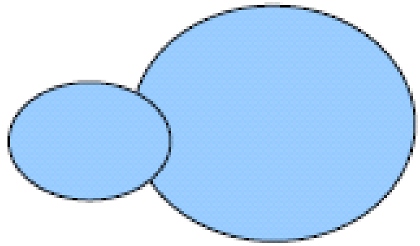
THREE MAIN STAGES :

CAPTURE
COMPLETE FUSION OR QUASIFISSION
DECAY OF CN

Capture=formation of di-nuclear system

Partial capture cross section for given **L** is:

$$\sigma_{cap} = \pi \lambda\!\!\!^{-2} (2L+1) P_{cap}(E_{c.m.}, L)$$



The distance between nuclei in DNS system is $R_{min}=R_1+R_2+0.5$ fm

where $$\lambda\!\!\!^{-2} = \hbar^2 / (2 \mu E_{c.m.})$$

$$E_{c.m.} = \frac{A_1 A_2}{A_1 + A_2} E_{lab}$$

and

$$P_{cap}(E_{c.m.}, L) = (1 + EXP(2\pi(V_b(L) - E_{c.m.})/h\omega_L)^{-1}$$

is a capture probability given by Hill-Wheeler.

$$L_{kin} \hbar = pb$$

b – impact parameter

p - momentum

Potential energy of DNS

$$U(R,Z,A,J) = B_1 + B_2 + V(R,Z,A,\beta_1,\beta_2,J) - [B_{12} + E_{12}^{rot}(J)],$$

$$V(R,Z,A,\beta_1,\beta_2,J) = V_C(R,Z,A,\beta_1,\beta_2) + V_N(R,Z,A,\beta_1,\beta_2) + \frac{\hbar^2 J(J+1)}{2\Im(R,A,\beta_1,\beta_2)}$$

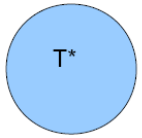
$$V_N = \int \rho_1(\mathbf{r_1})\rho_2(\mathbf{R}-\mathbf{r_2})F(\mathbf{r_1}-\mathbf{r_2})d\mathbf{r_1}d\mathbf{r_2},$$

where $F(\mathbf{r_1}-\mathbf{r_2}) = C_0[F_{\text{in}}\frac{\rho_0(\mathbf{r_1})}{\rho_{00}} + F_{\text{ex}}(1-\frac{\rho_0(\mathbf{r_1})}{\rho_{00}})]\delta(\mathbf{r_1}-\mathbf{r_2})$ is the Skyrme-type density-depending effective nucleon-nucleon interaction, which is known from the theory of finite Fermi systems [28], and $\rho_0(\mathbf{r}) = \rho_1(\mathbf{r}) + \rho_2(\mathbf{R}-\mathbf{r})$, $F_{\text{in,ex}} = f_{\text{in,ex}} + f'_{\text{in,ex}}\frac{(N-Z)(N_2-Z_2)}{(N+Z)(N_2+Z_2)}$. Here, $\rho_1(\mathbf{r_1})$ and $\rho_2(\mathbf{r_2})$, and N_2 (Z_2) are the nucleon densities of, respectively, the light and the heavy nuclei of the DNS, and neutron (charge) number of the heavy nucleus of the DNS.

Complete fusion

$$P_{CN} = \frac{\rho_{fus}}{\rho_{fus} + \rho_{qfiss} + \rho_{symm}}$$

Excited CN



EXITATION ENERGY OF CN:

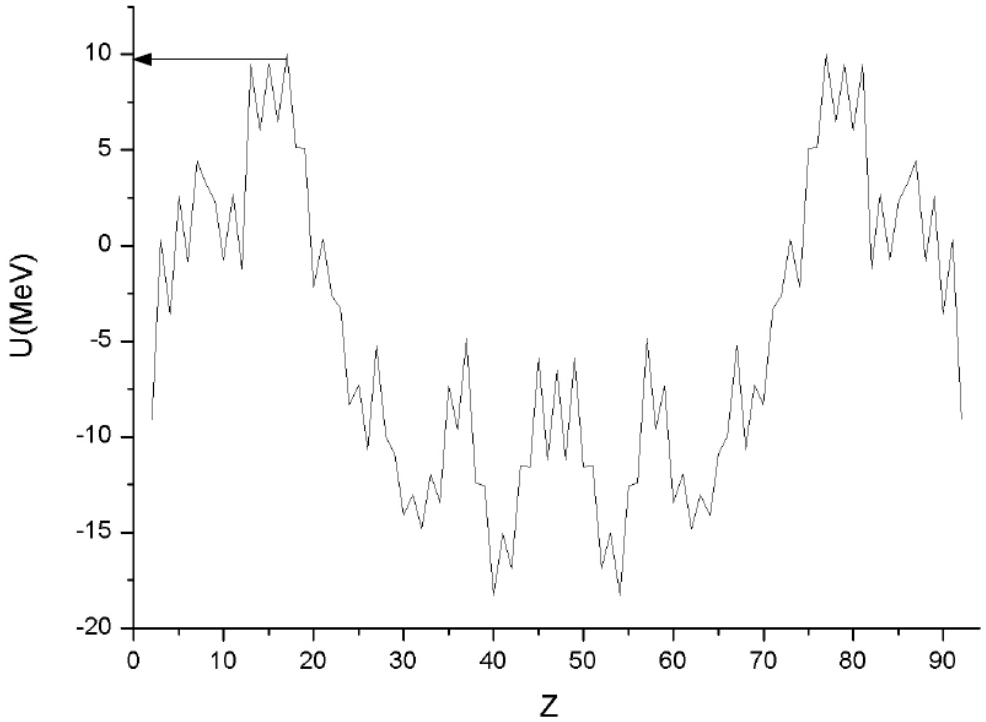
$$E_{ex} = E_{c.m.} + Q - E_{rot}(E_{c.m.}, b)$$

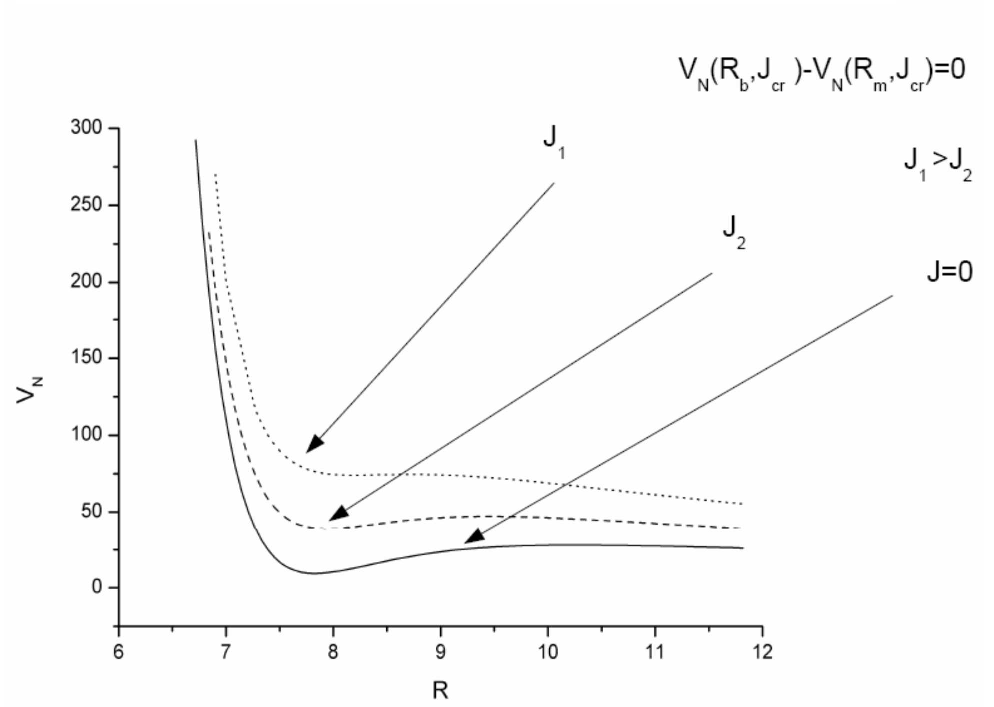
$$Q = B_1 + B_2 - B_{12}$$

$$E_{rot} = \frac{\hbar^2 J(J+1)}{2I}$$

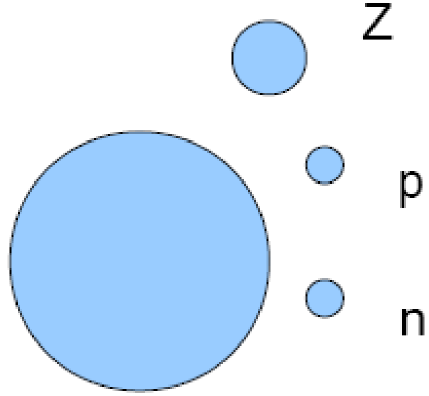
where I is the moment of inertia of CN

Driving potential for $^{25}Mg+^{206}Pb$ at J=20h





PARTICLE EMISSION AND FISSION



$$\sigma_i(E_{ex}, J) = \sum_{J=0}^{J_{max}} \sigma_{cap}(E_{c.m.}, J)\, P_{CN}(E_{c.m.}, J)\, P_i(E_{ex}, J)$$

where $P_i(E_{ex} J)$ is the probability of certain channel, *i* corresponds to particle emission and fission.

$$P_i(E_{ex}, J) = \frac{\Gamma_i}{\sum_i \Gamma_i}$$

Γ - decay width

Decay of excited CN by particle emission or binary decay

Corresponding weights for CN and DNS configurations:

$$P_{Z,A}(E^*_{CN},J) = \frac{\exp[-U(R_m,Z,A,J)/T_{CN}(J)]}{1+\sum_{Z'=2,A'}\exp[-U(R_m,Z',A',J)/T_{CN}(J)]}.$$

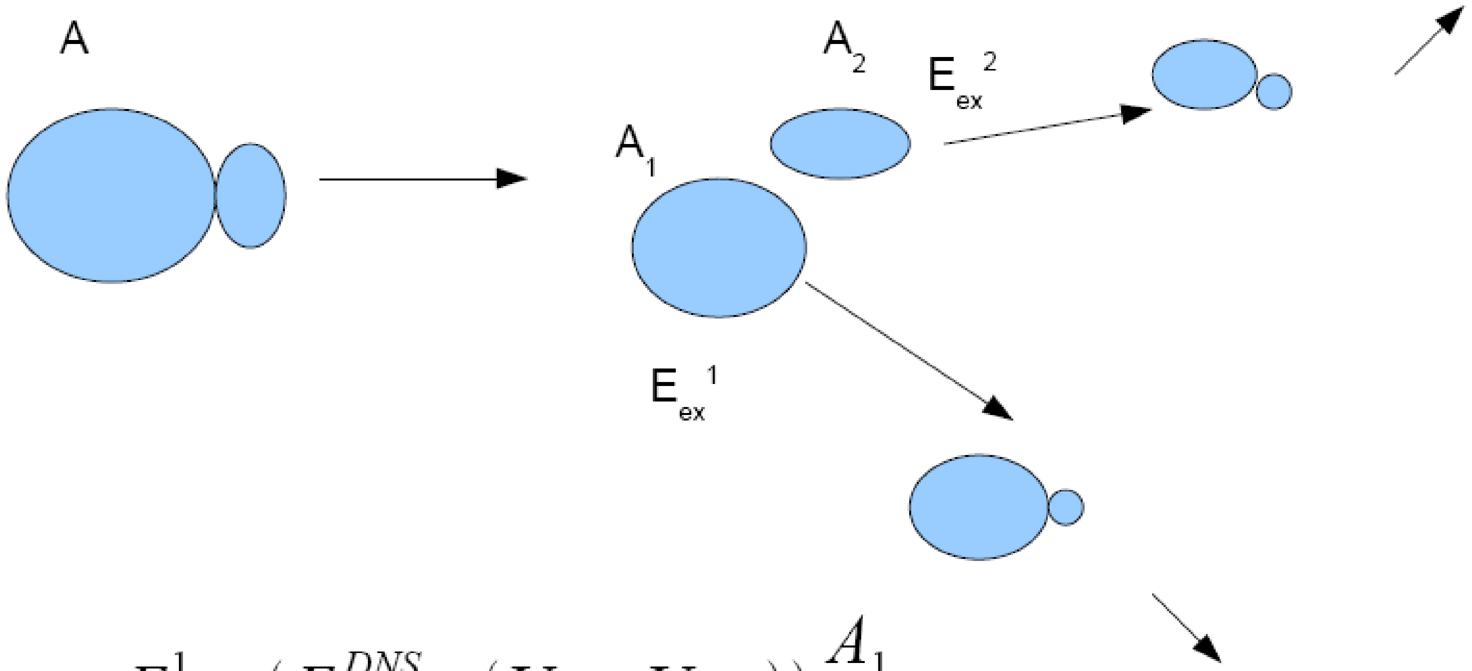
Particle emission from excited CN:

$$\Gamma_i = \frac{m_i R^2}{\pi\hbar^2\rho_{CN}(E^*_{CN})}\int_0^{E^*_{CN}-B_i}\rho_{res}(E^*_{CN}-B_i-\epsilon)\epsilon d\epsilon,$$

Decay probability of DNS can be written in complete analogy with the fission probability in the transition state formalism (at the high energy limit):

$$P^R_{Z,A} \sim \exp[-B^{qf}_R(Z,A,J)/T_{Z,A}(J)]$$

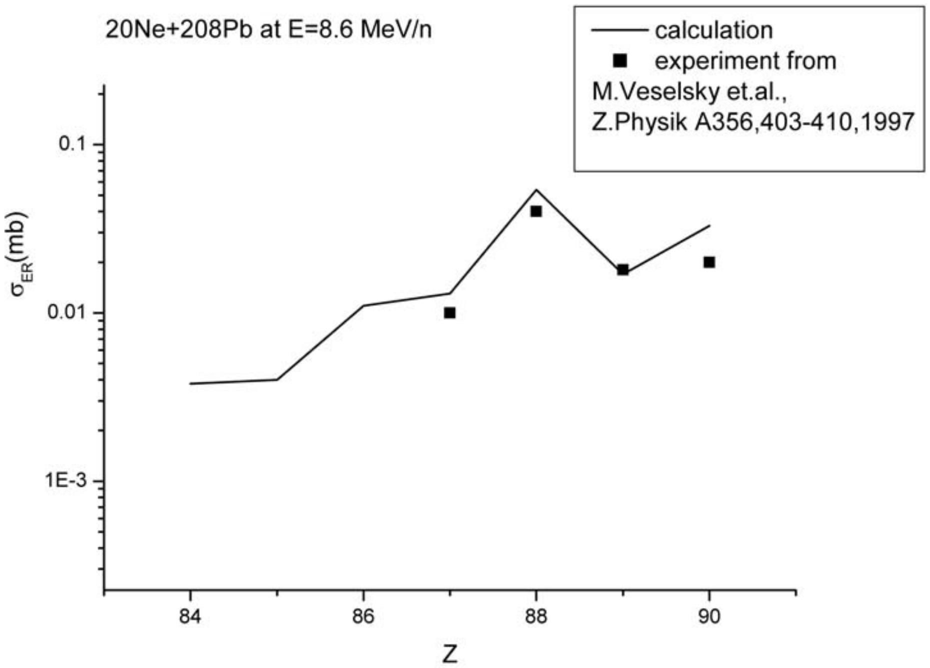
Cascade decay of excited CN is generated by Monte-Carlo method



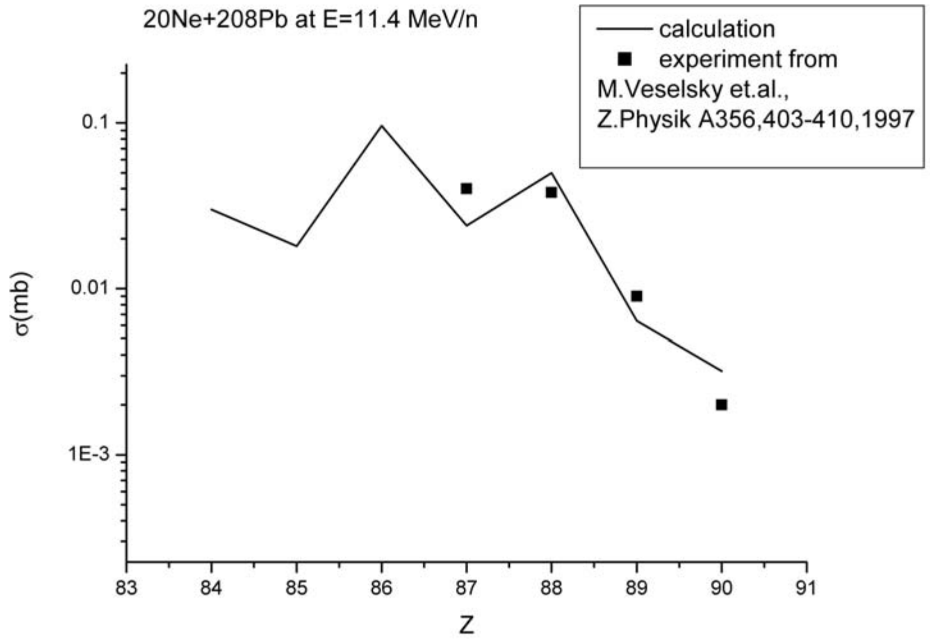
$$E_{ex}^{1}=(E_{ex}^{DNS}-(U_b-U_{min}))\frac{A_1}{A}$$

$$E_{ex}^{2}=(E_{ex}^{DNS}-(U_b-U_{min}))\frac{A_2}{A}$$

Results



20Ne+208Pb at E=8.6 MeV/n
calculation
experiment from
M.Veselsky et.al.,
Z.Physik A356,403-410,1997
0.1
0.01
1E-3
σER(mb)
84
86
88
90
Z



20Ne+208Pb at E=11.4 MeV/n
calculation
experiment from
M.Veselsky et.al.,
Z.Physik A356,403-410,1997
0.1
0.01
1E-3
σ(mb)
83
84
85
86
87
88
89
90
91
Z

TABLE I: The competition between ER-channels in $^{20}Ne+^{208}Pb$ at $E = 8.6$MeV/n($E^* = 98$MeV).

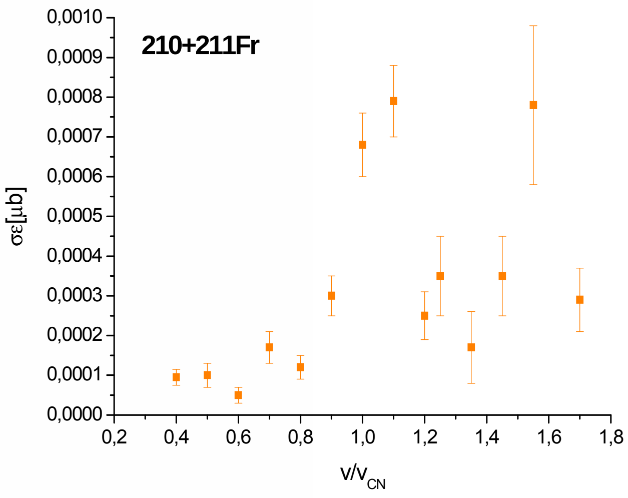
ER	Z	COMPETITION CHANNELS	Rate(percent)
Po	84	6n,2p,^{14}C	37
		8n,α,^{12}C	18
		8n,^{18}O	18
		6n,2p,3α	18
		6n,2p,α,^8Be	9
At	85	8n,1p,$^{12,14}C$	42
		7n,1p,3α	50
		7n,1p,α,^8Be	8
Rn	86	(10-9)n, $^{12,14}C$	12
		8n, 3α	40
		8n,^8Be,α	10
		8n,^8Be,2p	4
		8n,2p,2α	32
		6n,2p,2 $^{3,2}H$,α	2
Fr	87	7n,2p,$^{3,2}H$,α	10
		8n,1p,2α	90
Ra	88	10n,2α	37
		9n,2p,α	63

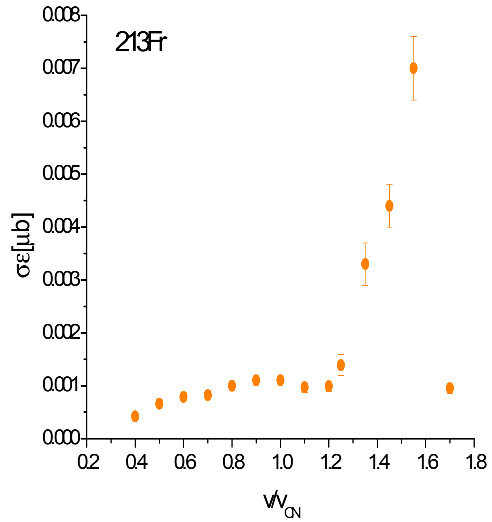
Calculation

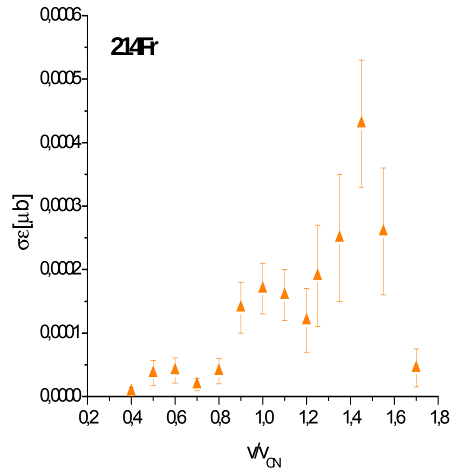
Experiment(GSI data)

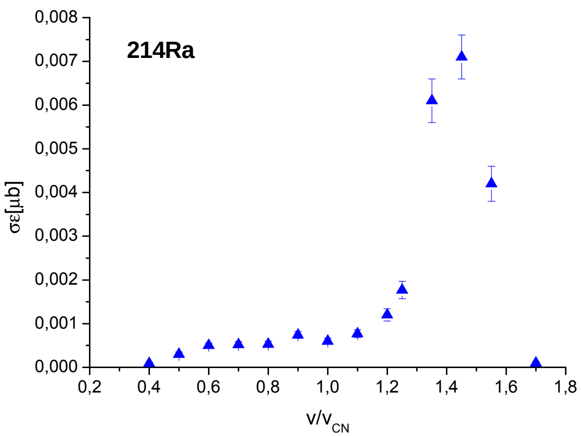
$^{25}Mg+^{206}Pb \rightarrow ^{231}Pu$ at 5.9MeV/n, E*=56 MeV

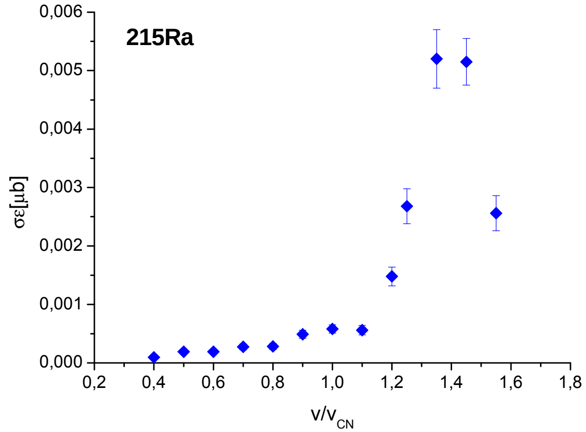
isotop	channel	velocity of ER
$^{210+211}Fr$ 3.1m	$^{3}H3n^{14}C$	$1.47v_{CN}$
^{212}Fr 20m	$^{2}H3n^{14}C$	$1.47v_{CN}$
^{213}Fr 34.6s	$^{14}C1p3n$	$1.47v_{CN}$
^{214}Fr 5ms	^{12}C 1p4n	$1.42v_{CN}$
$^{211+212}Ra$ 13s	$^{15}C4n$	$1.47\ v_{CN}$
^{213}Ra 2.7m	$^{14}C4n$	$1.47v_{CN}$
^{214}Ra 2.46s	$^{12}C5n$	$1.47v_{CN}$
^{215}Ra 1.59ms	$4n\ ^{12}C$	$1.42v_{CN}$

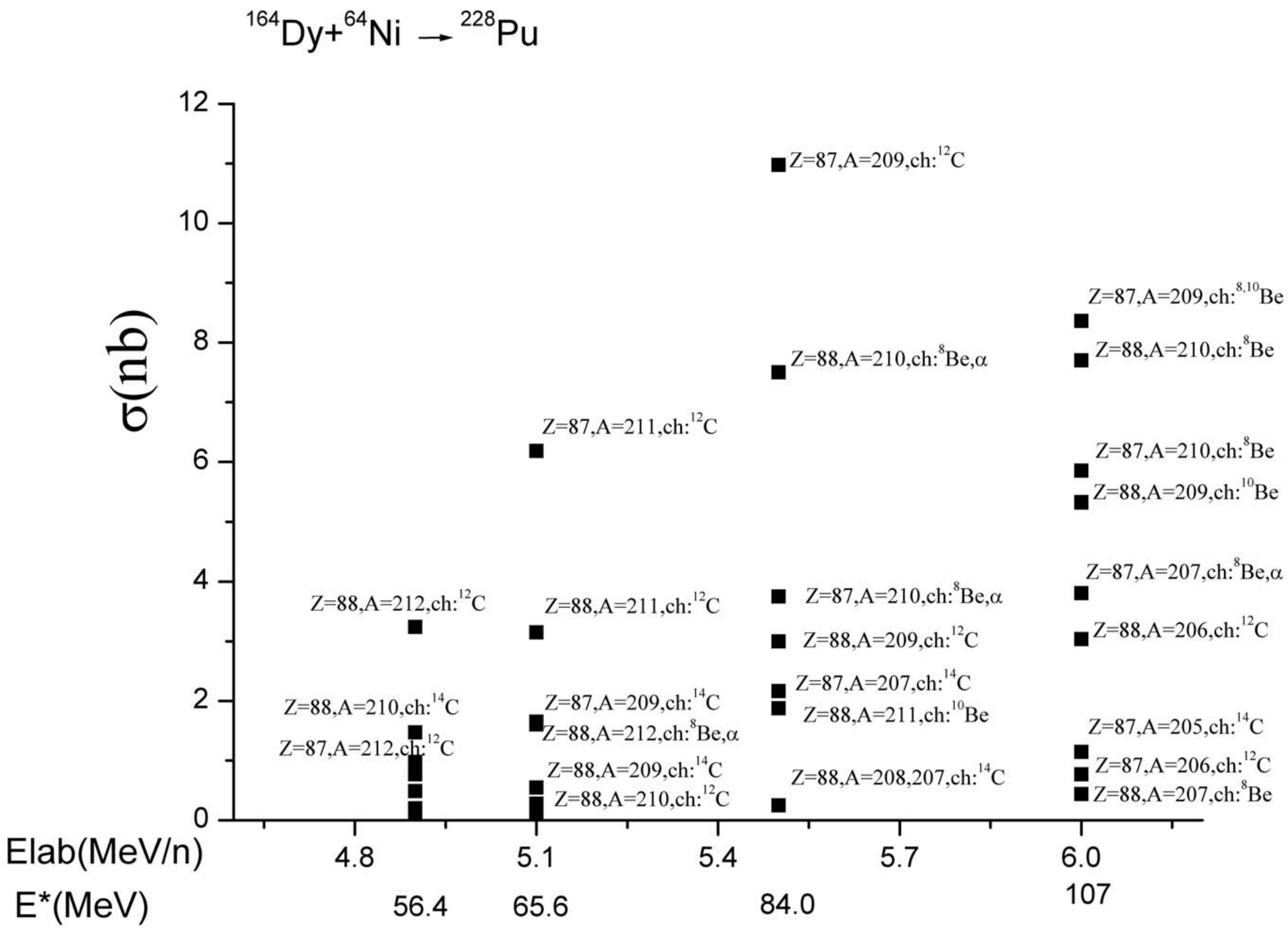




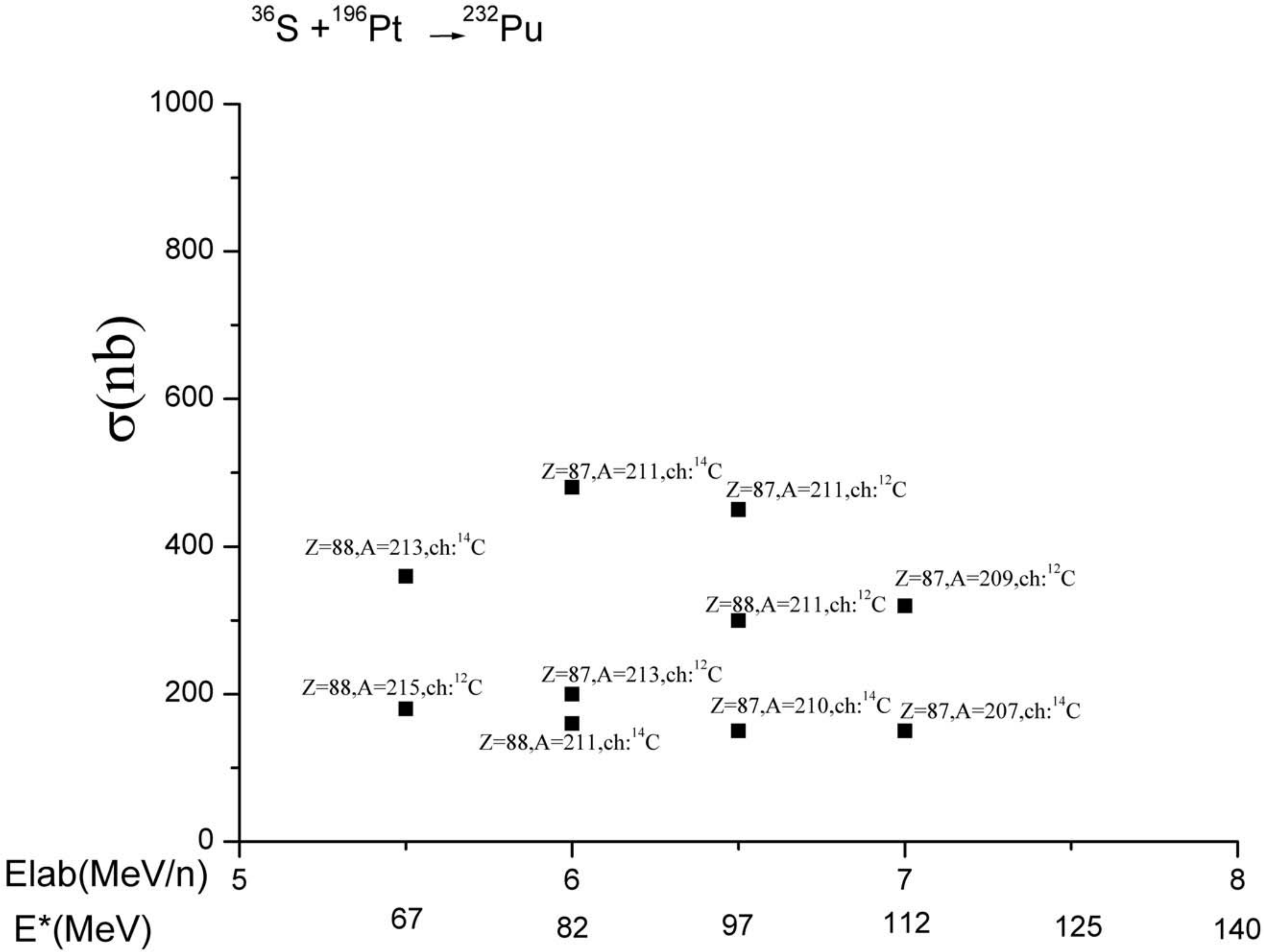






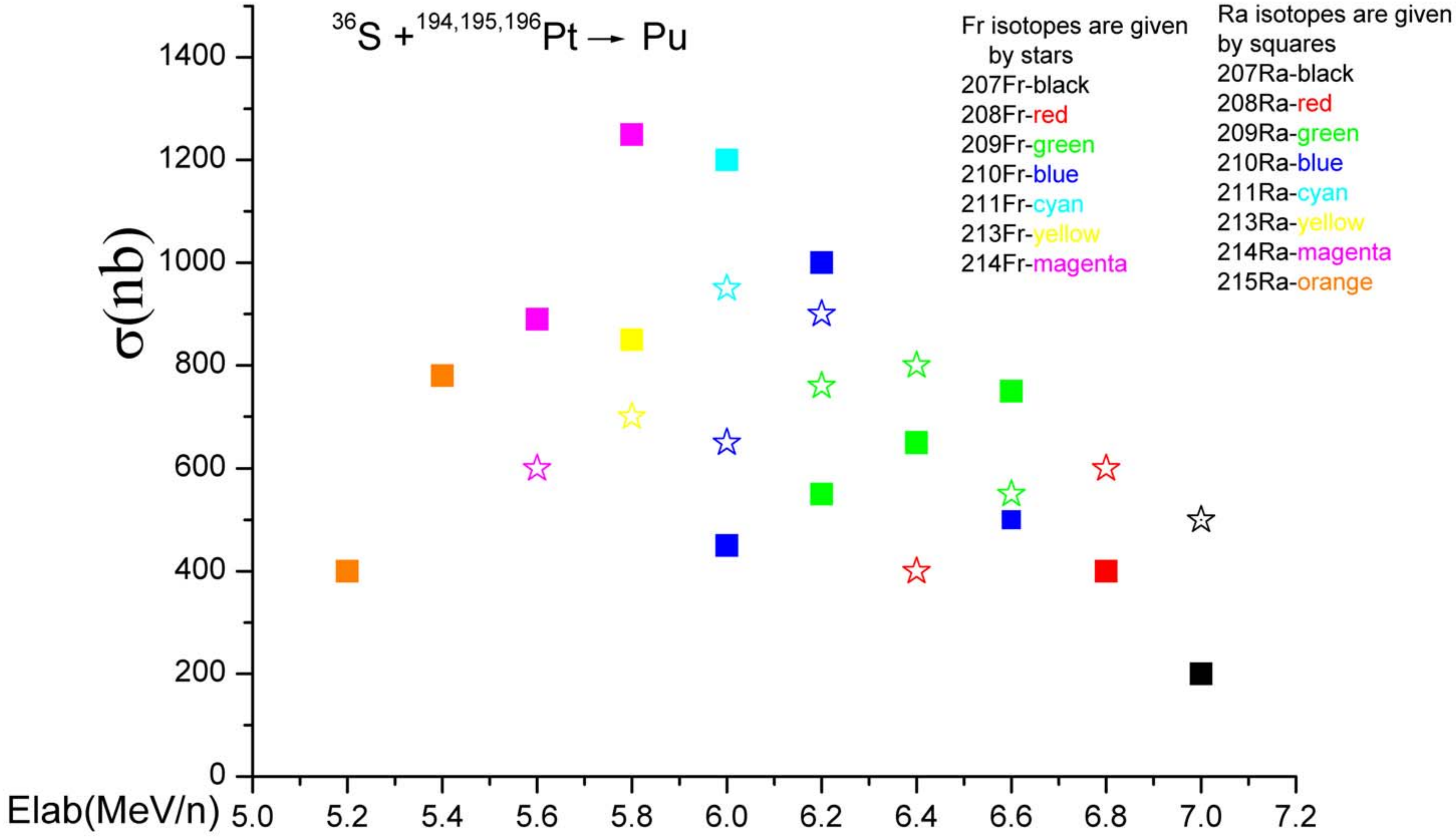


164Dy+64Ni → 228Pu
σ(nb)
Z=87,A=209,ch:12C
Z=87,A=209,ch:8,10Be
Z=88,A=210,ch:8Be,α
Z=88,A=210,ch:8Be
Z=87,A=211,ch:12C
Z=87,A=210,ch:8Be
Z=88,A=209,ch:10Be
Z=87,A=207,ch:8Be,α
Z=88,A=212,ch:12C
Z=88,A=211,ch:12C
Z=87,A=210,ch:8Be,α
Z=88,A=209,ch:12C
Z=88,A=206,ch:12C
Z=87,A=207,ch:14C
Z=88,A=210,ch:14C
Z=87,A=209,ch:14C
Z=88,A=211,ch:10Be
Z=88,A=212,ch:8Be,α
Z=87,A=205,ch:14C
Z=87,A=212,ch:12C
Z=88,A=209,ch:14C
Z=87,A=206,ch:12C
Z=88,A=208,207,ch:14C
Z=88,A=210,ch:12C
Z=88,A=207,ch:8Be
Elab(MeV/n)
E*(MeV)
56.4
65.6
84.0
107



$^{36}S + ^{196}Pt \rightarrow ^{232}Pu$
σ(nb)
1000
800
600
400
200
0
Z=87,A=211,ch:^{14}C
Z=87,A=211,ch:^{12}C
Z=88,A=213,ch:^{14}C
Z=87,A=209,ch:^{12}C
Z=88,A=211,ch:^{12}C
Z=87,A=213,ch:^{12}C
Z=88,A=215,ch:^{12}C
Z=87,A=210,ch:^{14}C
Z=87,A=207,ch:^{14}C
Z=88,A=211,ch:^{14}C
Elab(MeV/n)
5
6
7
8
E*(MeV)
67
82
97
112
125
140

Fr and Ra isotopes which are produced by ^{12}C, ^{14}C emission from CN



Conclusions

Evaporation residue's cross sections in heavy ion collisions can be described very well within the DNS model.

The GSI data of momentum distributions of ER's shows a peaks at velocities far from compound nucleus velocity, which can be described as ER's after heavy cluster emission or binary decay from very asymmetric DNS configuration.

Optimal bombarding energy for different reactions for obtaining ER's via cluster emission is under investigation.