Влияние α–кластеризации на предравновесную эмиссию α–частиц в реакциях с тяжёлыми ионами.

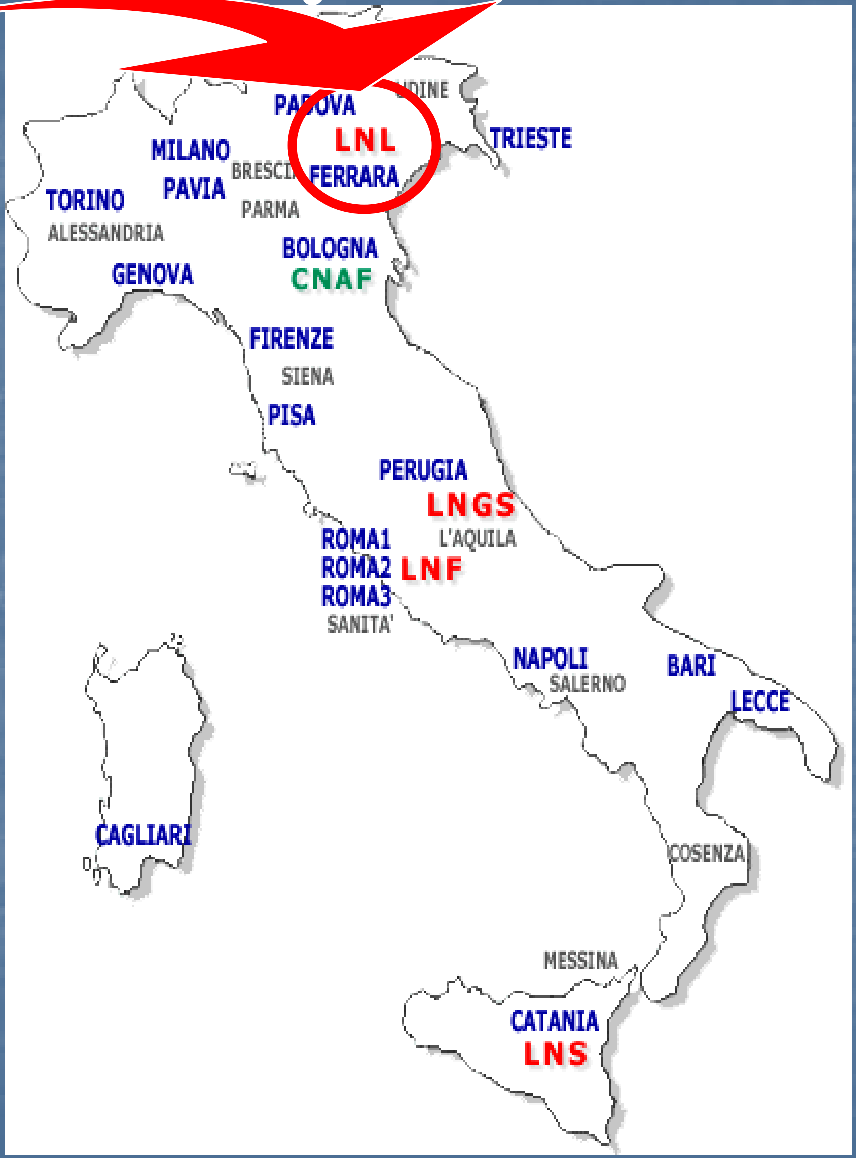
Light Particle Emission Mechanisms in Heavy-Ion Reactions at 5-20 MeV/u

PRE-EQUILIBRIUM α–PARTICLE EMISSION AS A PROBE TO STUDY α–CLUSTERING IN NUCLEI

NUCL-EX COLLABORATION

LNL - INFN - Identity Card

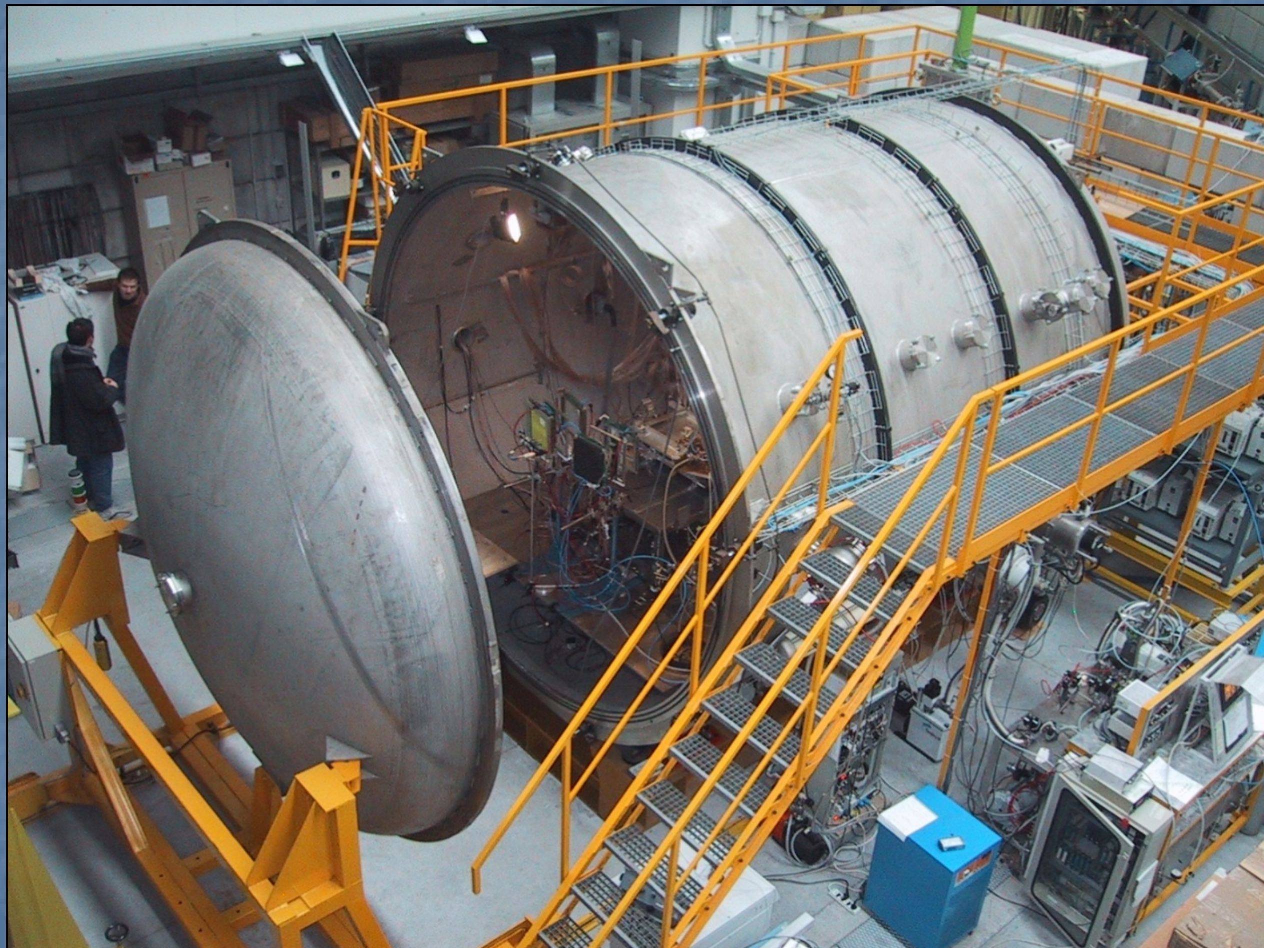
MULTI TASK
MULTI DISCIPLINARY
But mainly
Nuclear Physics Based
User Oriented
Laboratories



Laboratori Nazionali di Legnaro: year 2000

G. AR. F. I. E. L. D.

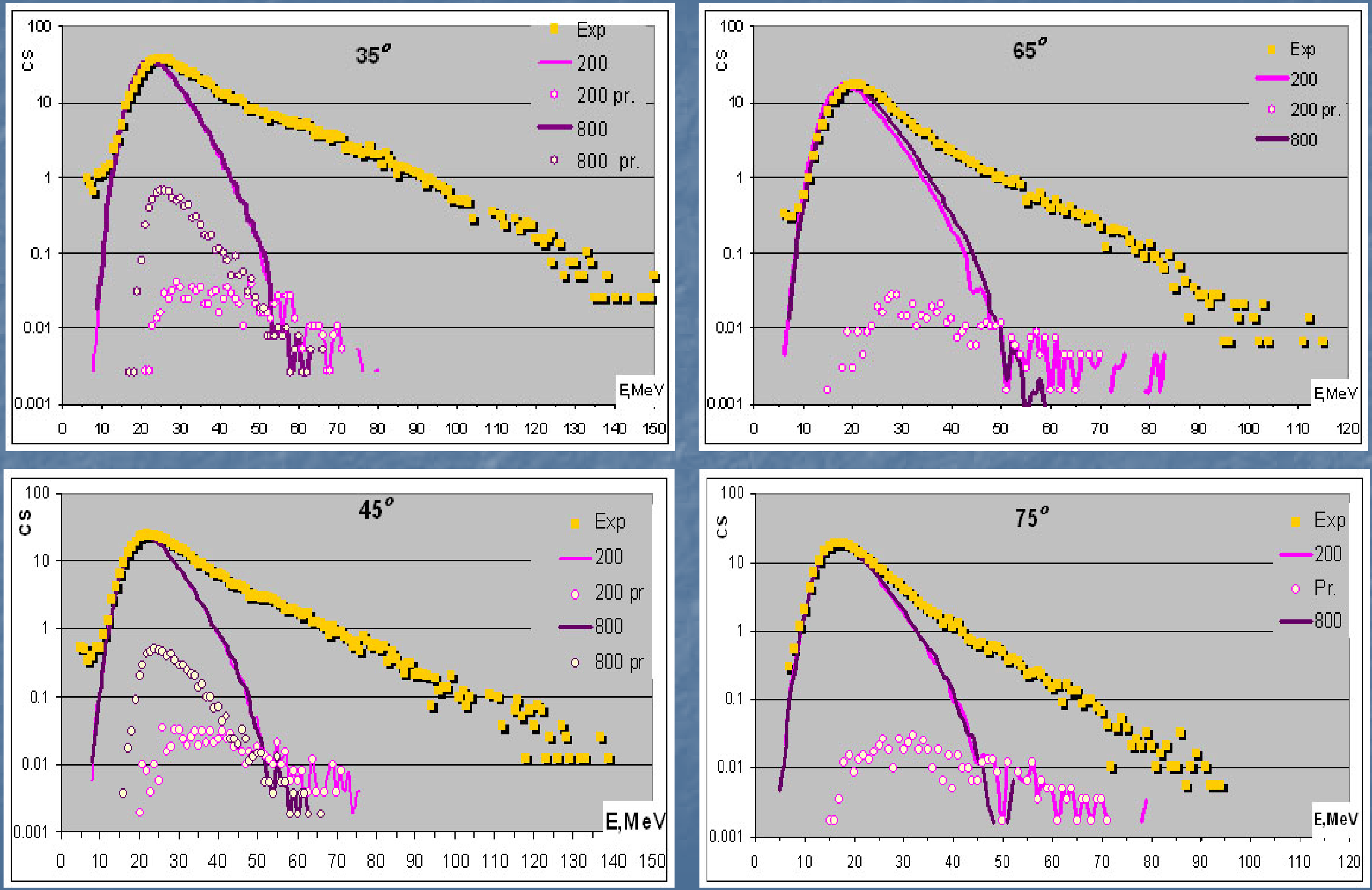
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions



Systems studied

Reaction	E_{BEAM} MeV/u	E_{CM} MeV	E^*_{CN} MeV	v_{BEAM} cm/ns	v_{CN} cm/ns
$^{64}Ni+^{68}Zn$	4.7	155	100	3.01	1.46
$^{64}Ni+^{68}Zn$	*6.3*	206	151	3.48	1.69
$^{64}Ni+^{68}Zn$	7.8	258	203	3.89	1.88
$^{16}O+^{116}Sn$ (130 МэВ)	8.1	114	100	3.96	0.48
$^{16}O+^{116}Sn$ (250 МэВ)	15.6	220	206	5.49	0.67

α, $^{16}O+^{116}Sn$, $E_O=250$ MeV$_{(start)}$



			250 МэВ		σ= 1637			N=							Np=16	Nh=0
N	σ_{tot}	n	p	α	n/tot	p/tot	α/tot	1.4-(p+α)	n/p	n/α	p/α	Ключ	a	Δ		/M**2
1	1633.87	712.2	586.26	335.41	0.436	0.359	0.205	0.836	1.215	2.123	1.748	4,5	A/8	Grudz		
2	1636.64	761.83	622.31	252.5	0.465	0.380	0.154	0.865	1.224	3.017	2.465	2,3	A/8	12/A**.5		
3	1636.55	750.24	612.48	273.83	0.458	0.374	0.167	0.858	1.225	2.740	2.237	0,1	A/8	0	400	8.45E-07
4	1636.66	731.19	609.29	296.18	0.447	0.372	0.181	0.847	1.200	2.469	2.057	6,7	Grudz	0		
5	1636.66	691.07	583.45	362.14	0.422	0.356	0.221	0.822	1.184	1.908	1.611	8,9	Grudz	Grudz		
6	1636.65	695.94	583.64	357.07	0.425	0.357	0.218	0.825	1.192	1.949	1.635				600	1.27E-06
7	1636.67	689.87	583.40	363.40	0.422	0.356	0.222	0.822	1.182	1.898	1.605				350	7.40E-07
8	1636.67	683.97	583.05	369.65	0.418	0.356	0.226	0.818	1.173	1.850	1.577				100	2.11E-07
9	1636.53	700.90	583.70	351.93	0.428	0.357	0.215	0.828	1.201	1.992	1.659				800	1.69E-06
	≡	N 5										$\langle E\rangle_n$	$\langle E\rangle_p$	$\langle E\rangle_\alpha$	Np	Nh
10	1636.66	681.91	576.19	378.56	0.417	0.352	0.231	0.817	1.183	1.801	1.522	18.856	27.776	35.346	15	1
11	1636.67	672.21	568.29	396.17	0.411	0.347	0.242	0.811	1.183	1.697	1.434	18.893	27.821	35.406	14	2
12	1636.66	651.01	550.37	435.28	0.398	0.336	0.266	0.798	1.183	1.496	1.264	18.906	27.847	35.463	12	4
5	1636.66	691.07	583.45	362.14	0.422	0.356	0.221	0.822	1.184	1.908	1.611	18.800	27.710	35.266	16	0
13	1636.66	699.96	581.02	355.68	0.428	0.355	0.217	0.828	1.205	1.968	1.634	17.796	26.602	34.104	16	1
14	1636.57	758.66	565.13	312.78	0.464	0.345	0.191	0.864	1.342	2.426	1.807	12.690	21.017	28.314	16	8
15	1635.79	791.66	555.88	288.25	0.484	0.340	0.176	0.884	1.424	2.746	1.928	10.691	18.841	26.114	16	12
16	1636.66	430.40	475.32	730.94	0.263	0.290	0.447	0.663	0.905	0.589	0.650	45.322	55.540	61.923	4	0
17	1636.66	458.50	467.60	710.56	0.280	0.286	0.434	0.680	0.981	0.645	0.658	34.728	45.181	52.874	4	3
		err	err	err								err	err	err	4	12
		err	err	err								err	err	err	4	4

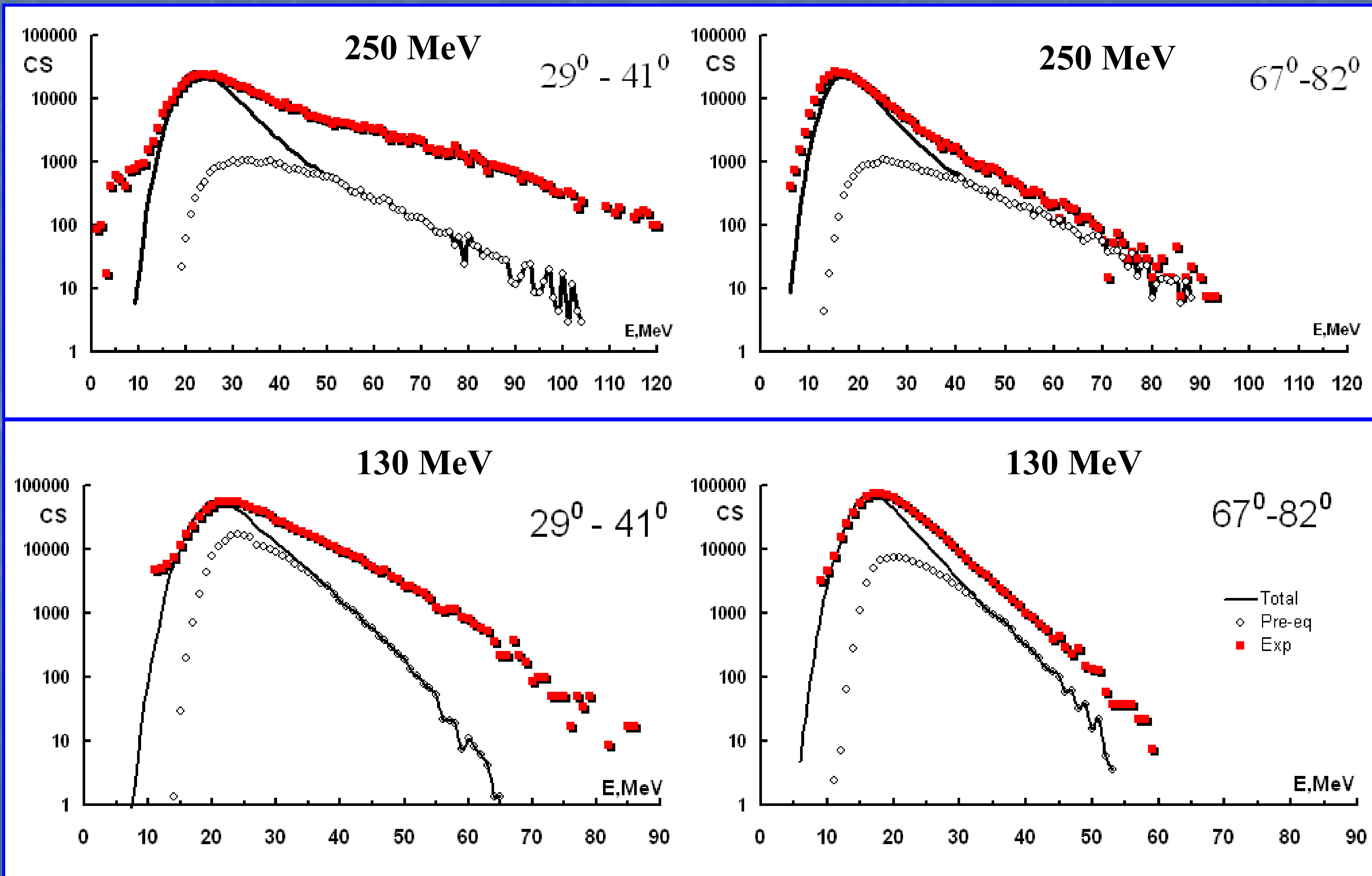
			≡ N 5		Np=16	Nh=1		250 МэВ							
	V	*E	*E**2	R0R	ARD	R0C	W0	*E	*E**2	R01	AID	NPD		IRAD	
n	47.01	-0.267	-0.002	1.273	0.660	0.000	9.520	-0.053	0	1.278	0.48	250	SURF	1	*o*
p	**55.842**	-0.550	0	1.250	0.650	1.250	**13.500**	0.000	0	1.250	0.47	250	SURF	1	*l*
α	189.057	-0.248	0	1.245	0.774	1.300	3.955	0.200	0	1.570	0.59	250	VOL	1	*d*
n	53.391	-0.32	0	1.17	0.75	0.00	11.545	-0.25	0	6.415	0.580	250	SURF	1	*new*
p	61.466	-0.32	0	1.17	0.75	1.25	13.255	-0.25	0	6.720	0.595	250	SURF	1	
α	170.039														
p	61.13														

N	σ_{tot}	n	p	α	n/tot	p/tot	α/tot	1.4-(p+α)	n/p	n/α	p/α	$\langle E\rangle_n$	$\langle E\rangle_p$	$\langle E\rangle_\alpha$	
Nev	1636.66	692.10	572.32	372.24	0.423	**0.350**	**0.227**	**0.823**	1.209	1.859	1.538	15.030	22.941	34.097	250
Old	1636.66	699.96	581.02	355.68	0.428	**0.355**	**0.217**	**0.828**	1.205	1.968	1.634	17.796	26.602	34.104	

Motivation

Our recent work, based on the results from the GARFIELD + HECTOR experiment at LNL, Legnaro and related to the α-particles emission in the **250** and **130** MeV **$^{16}O+^{116}Sn$** reactions, brought to the conclusion that a pronounced production of α - particle have been observed which can be ascribed to α clustering in the projectile nucleus. These are linked to the production of secondary alpha particles during non-equilibrium stage of fusion nuclear reaction

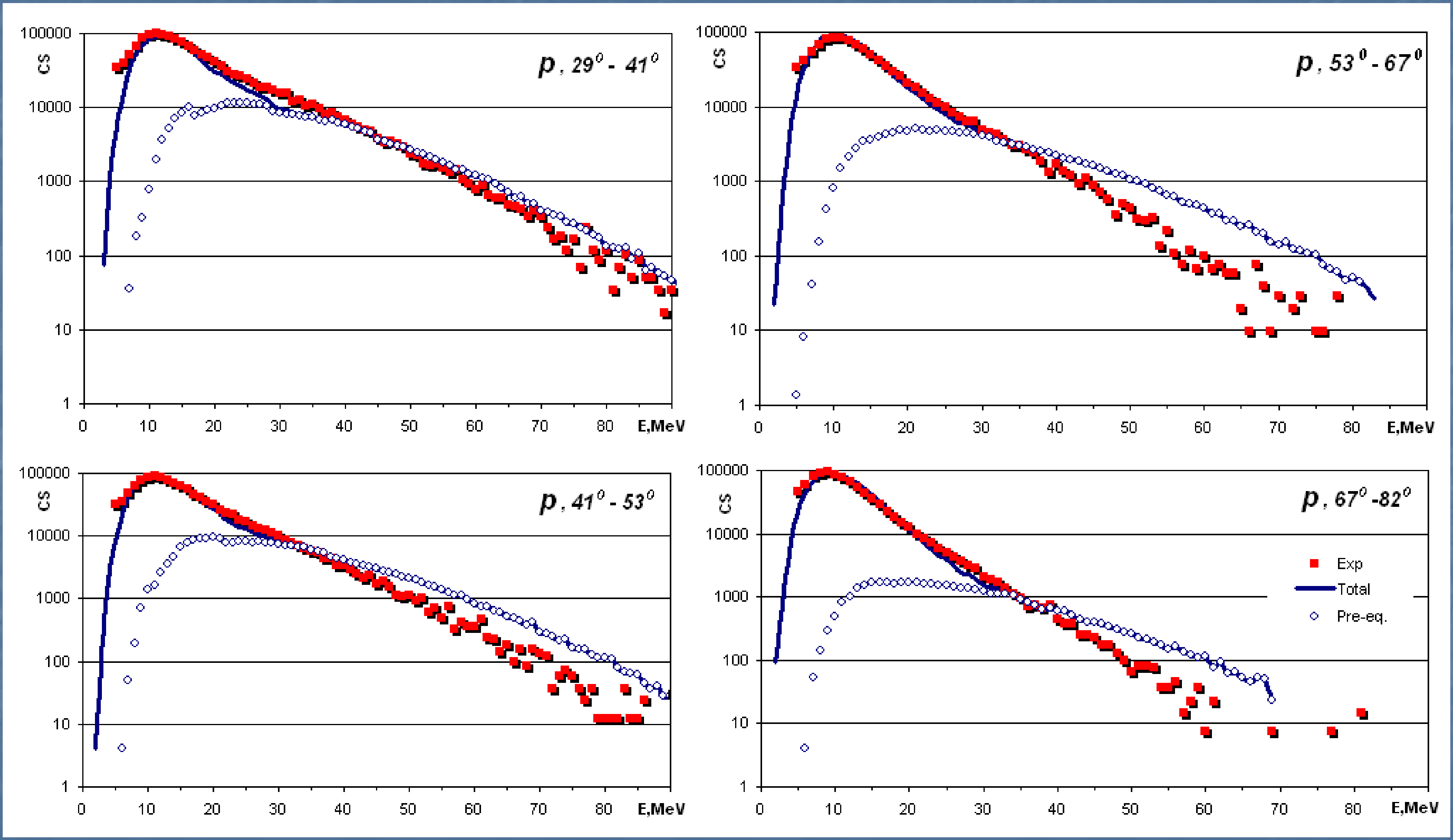
$^{16}O+^{116}Sn$



Illustration

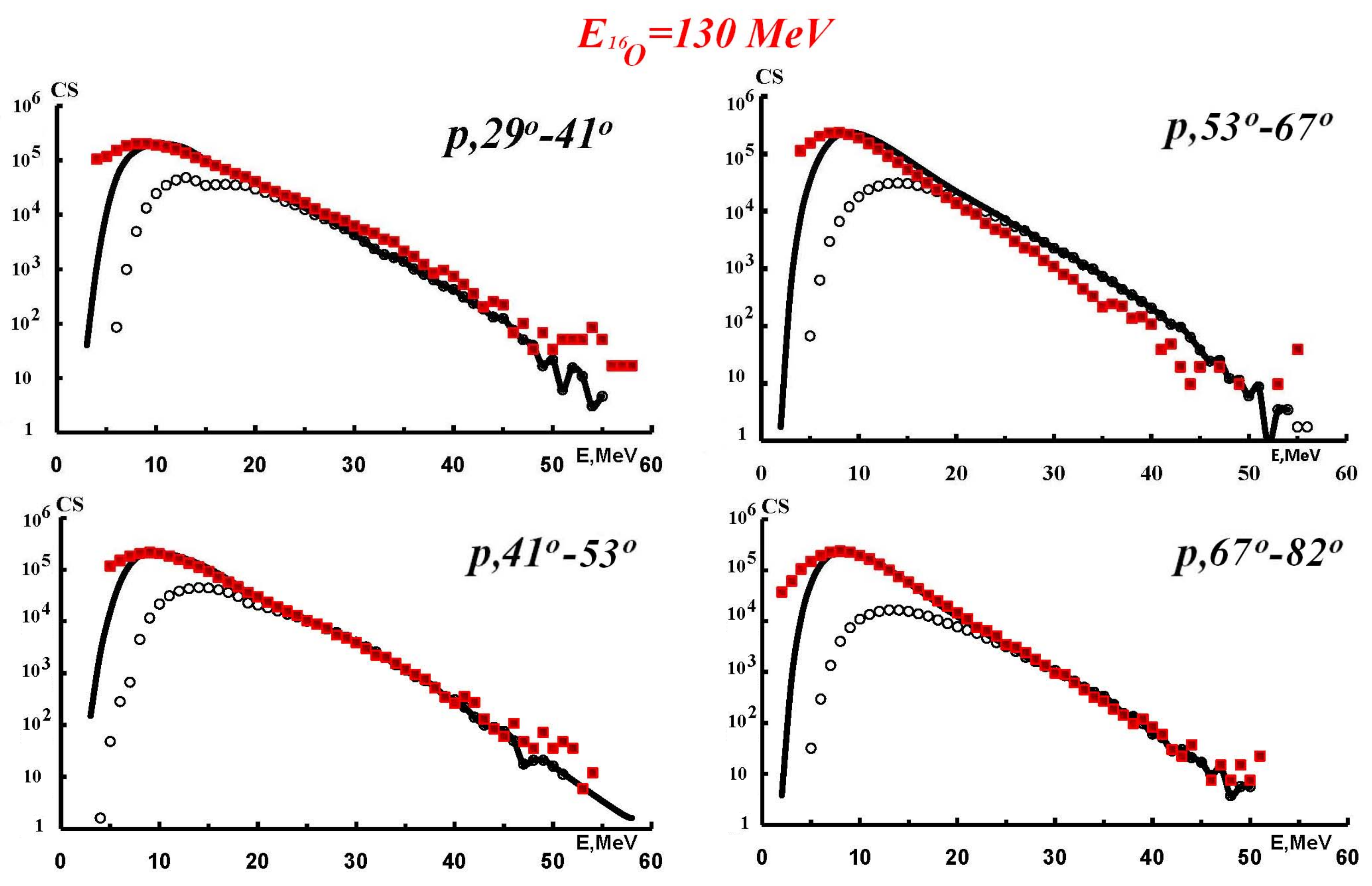
E(^{16}O)=250 MeV

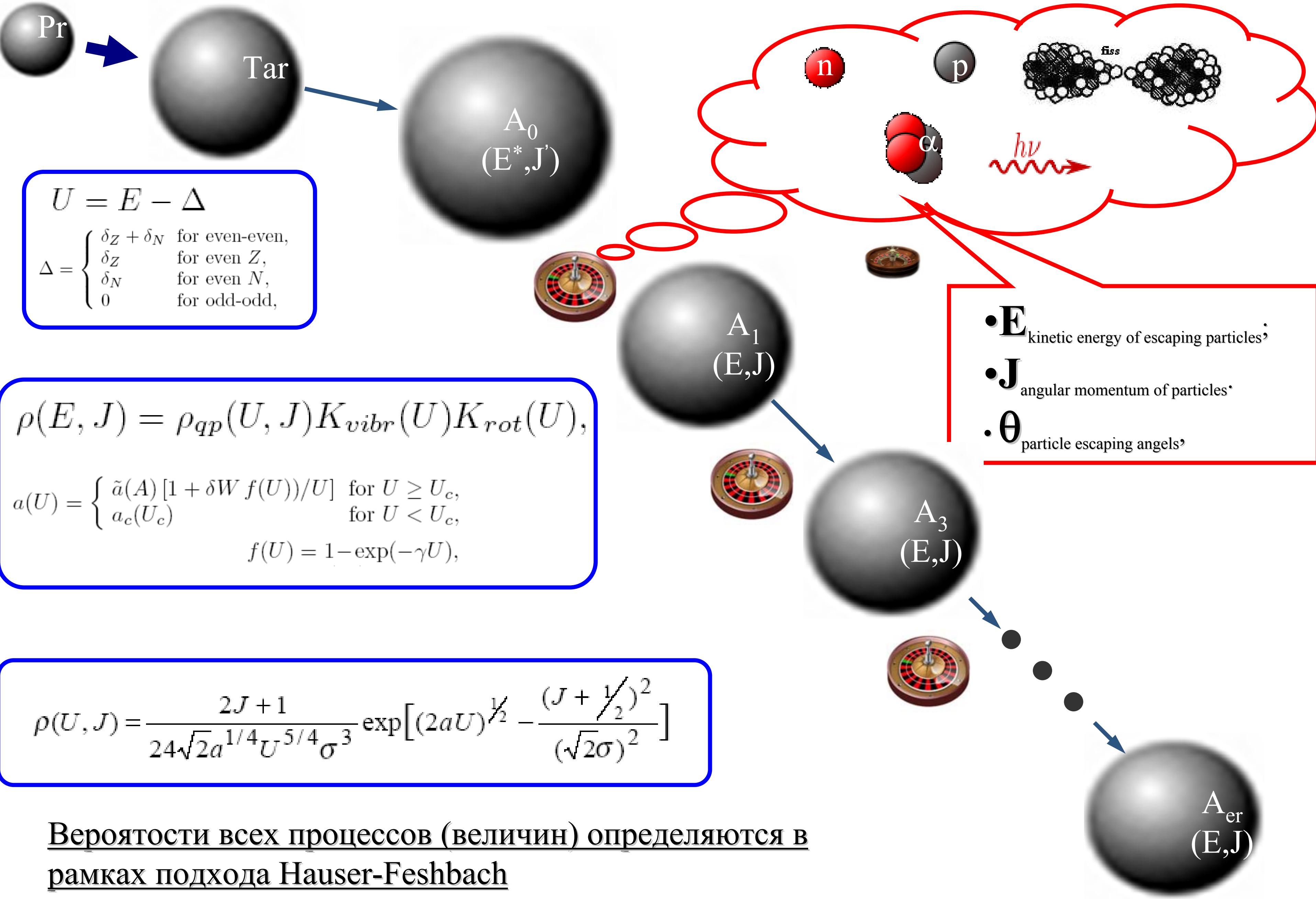
^{16}O+^{116}Sn



Illustration

$^{16}O+^{116}Sn$





$$U = E - \Delta$$

$$\Delta = \begin{cases} \delta_Z + \delta_N & \text{for even-even,} \\ \delta_Z & \text{for even } Z, \\ \delta_N & \text{for even } N, \\ 0 & \text{for odd-odd,} \end{cases}$$

$$\rho(E,J) = \rho_{qp}(U,J) K_{vibr}(U) K_{rot}(U),$$

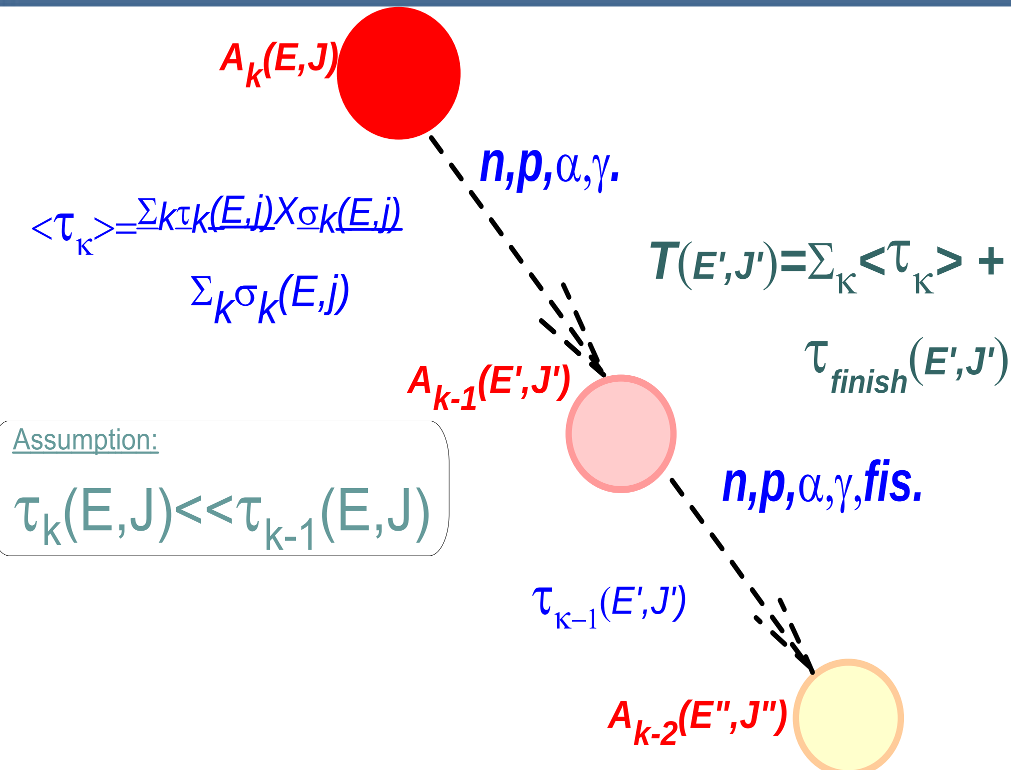
$$a(U) = \begin{cases} \tilde{a}(A)\left[1 + \delta W\, f(U))/U\right] & \text{for } U \geq U_c, \\ a_c(U_c) & \text{for } U < U_c, \end{cases}$$

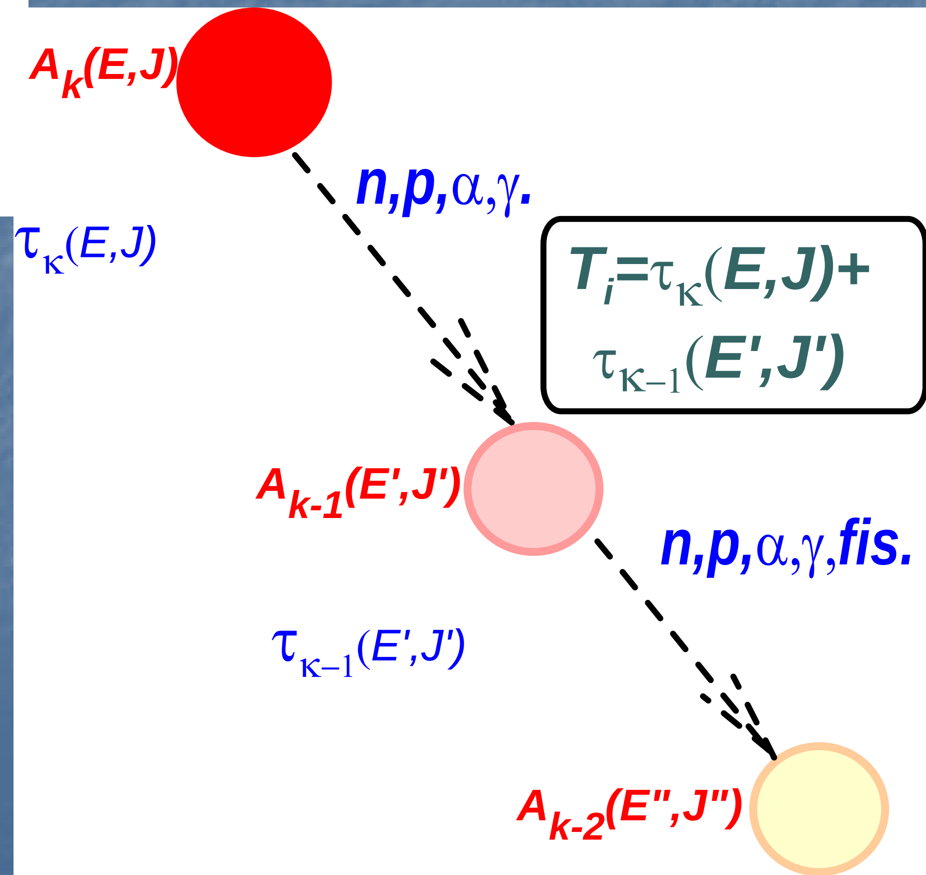
$$f(U) = 1 - \exp(-\gamma U),$$

$$\rho(U,J) = \frac{2J+1}{24\sqrt{2}a^{1/4}U^{5/4}\sigma^3} \exp\left[(2aU)^{1/2} - \frac{(J+1/2)^2}{(\sqrt{2}\sigma)^2}\right]$$

Вероятости всех процессов (величин) определяются в рамках подхода Hauser-Feshbach

code PACE





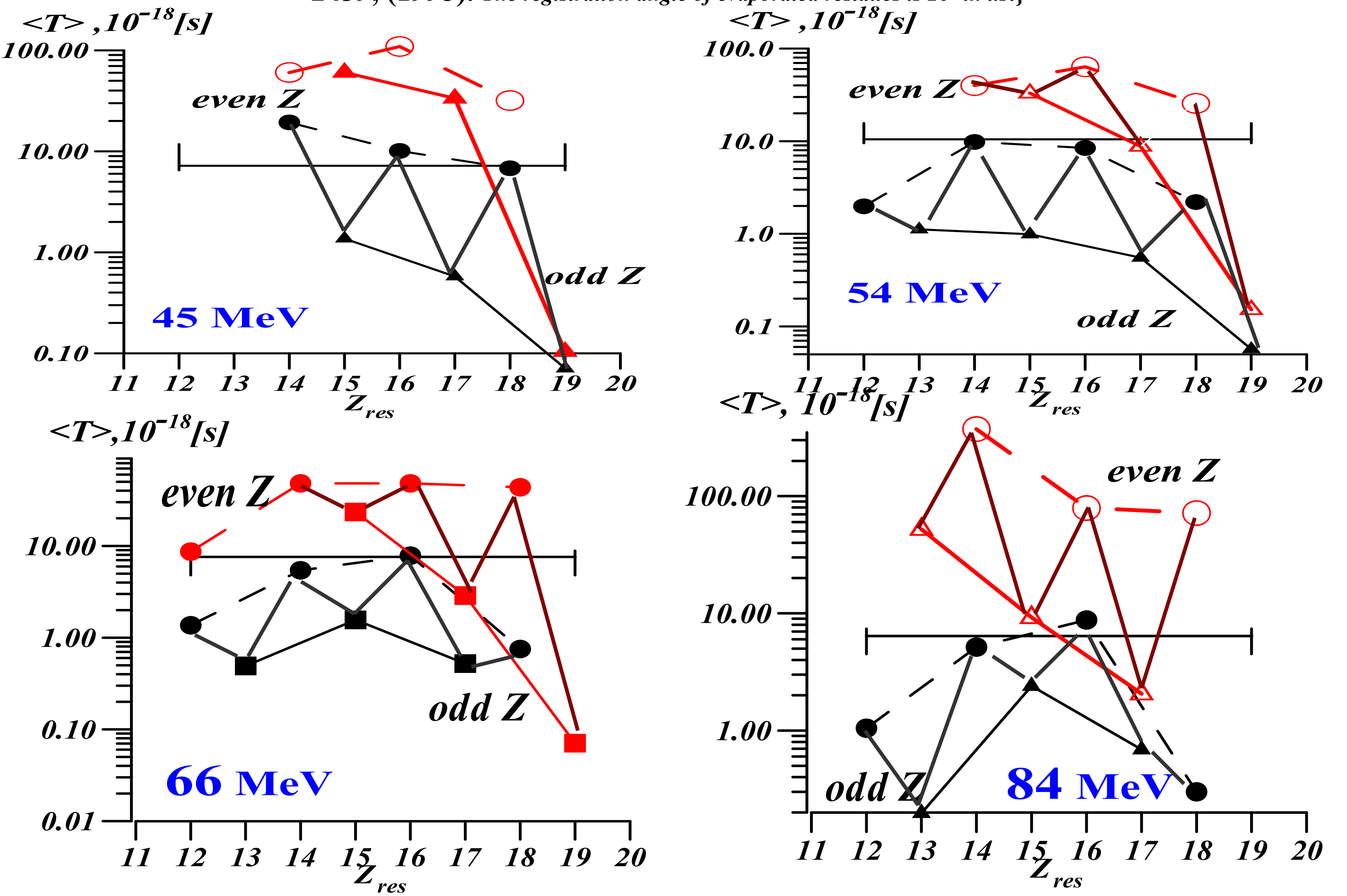
Стандартное выражение для времени жизни $\tau_k(E,J)$ возбужденного промежуточного ядра, обозначенного индексом **k**, с энергией **E** и моментом **J** есть:

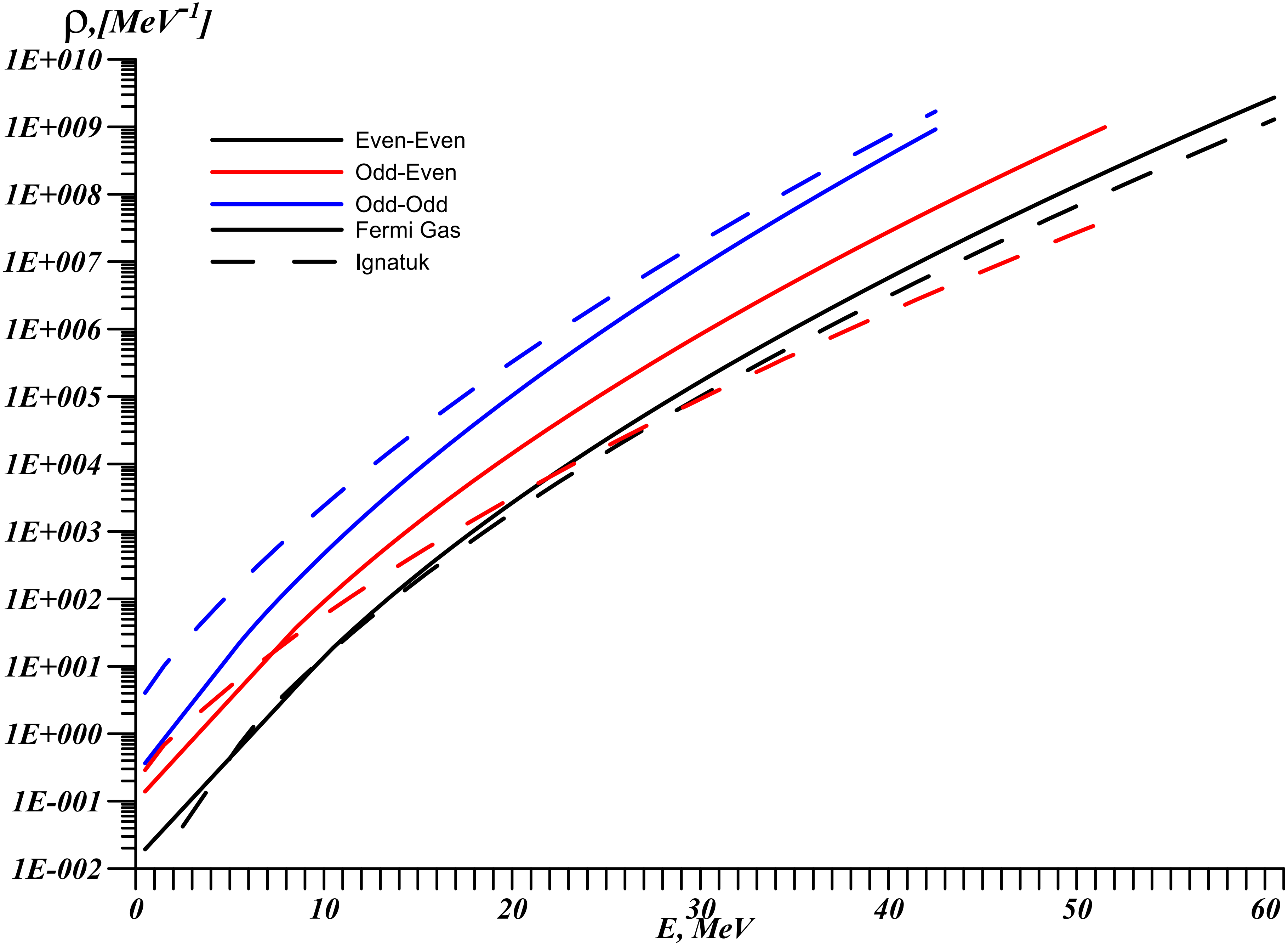
$$\tau_k(E,J) = \hbar/\Gamma_k(E,J), \qquad (1)$$

$$T_i = \sum_k \tau_k(E,J). \qquad (2)$$

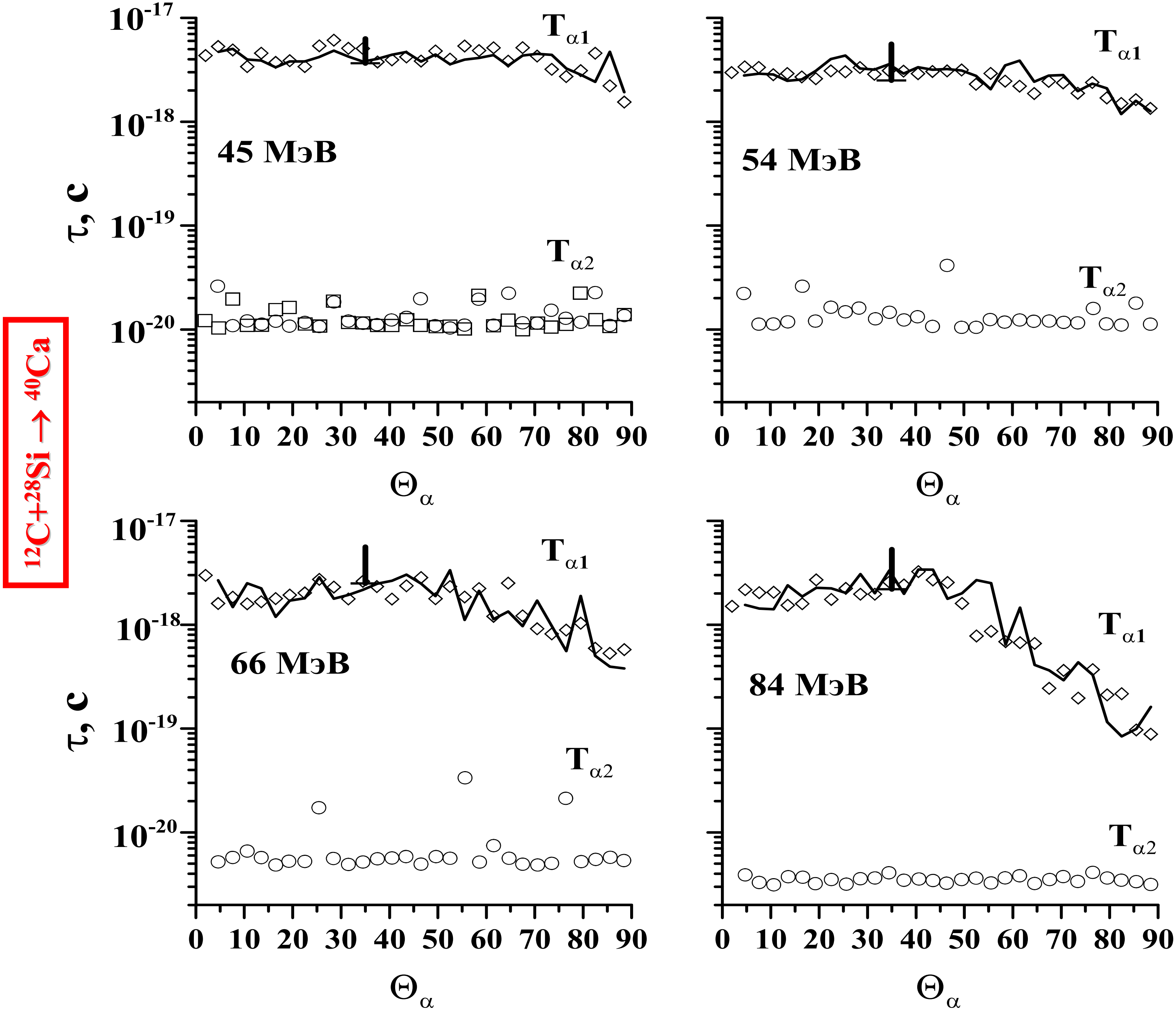
«Четно-нечетные» эффекты временных характеристик [Staggering effect]

$^{12}C+^{28}Si \rightarrow ^{40}Ca$ (E (^{12}C) = 45, 54, 66, 84 MeV) {Vandana Nanal et al., Phys. Rev. C 51, 2439, (1995). *The registration angle of evaporated residues is 20^0 in l.s.*}

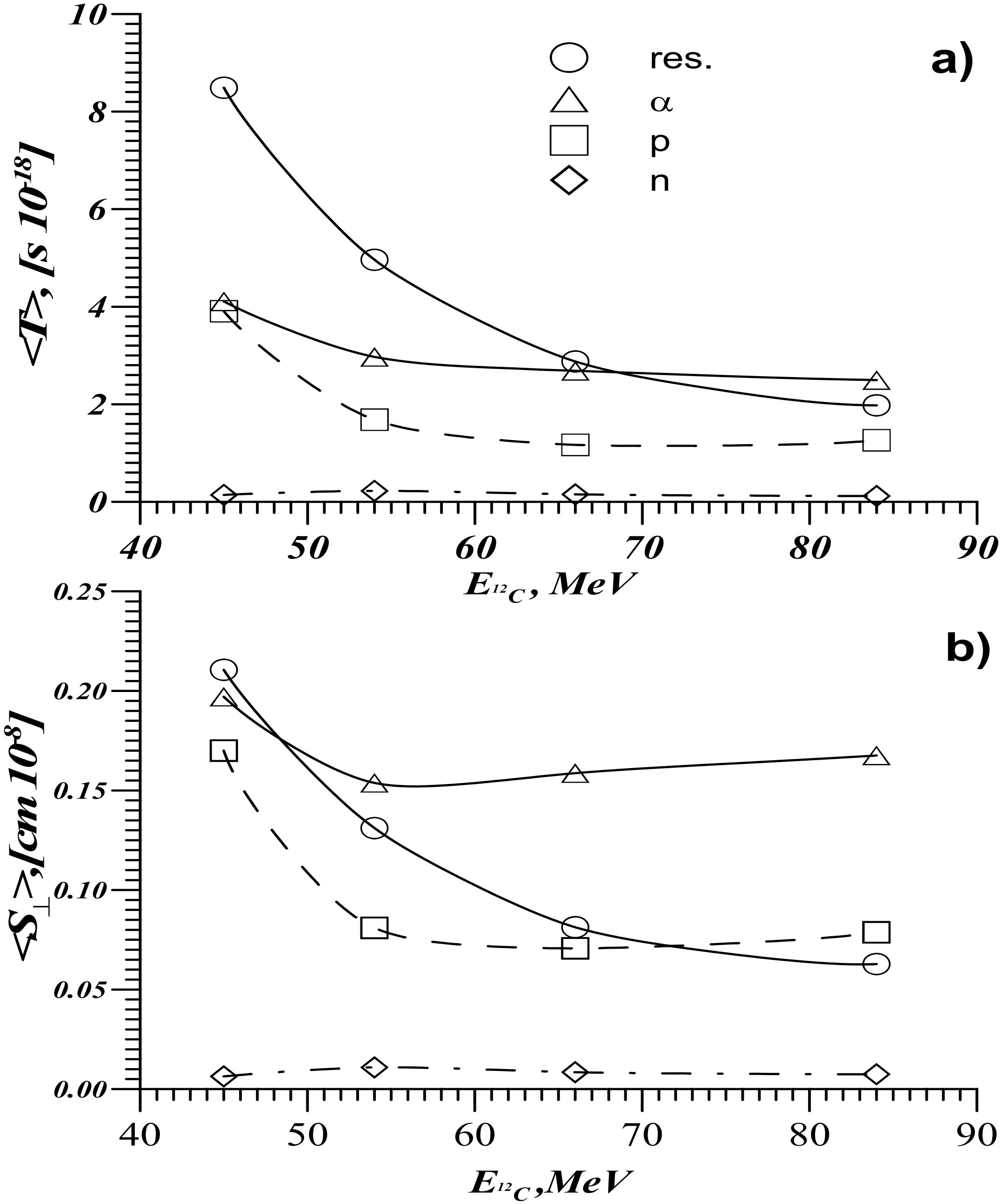




ρ,[MeV⁻¹]
1E+010
1E+009
1E+008
1E+007
1E+006
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Even-Even
Odd-Even
Odd-Odd
Fermi Gas
Ignatuk
0
10
20
30
40
50
60
E, MeV



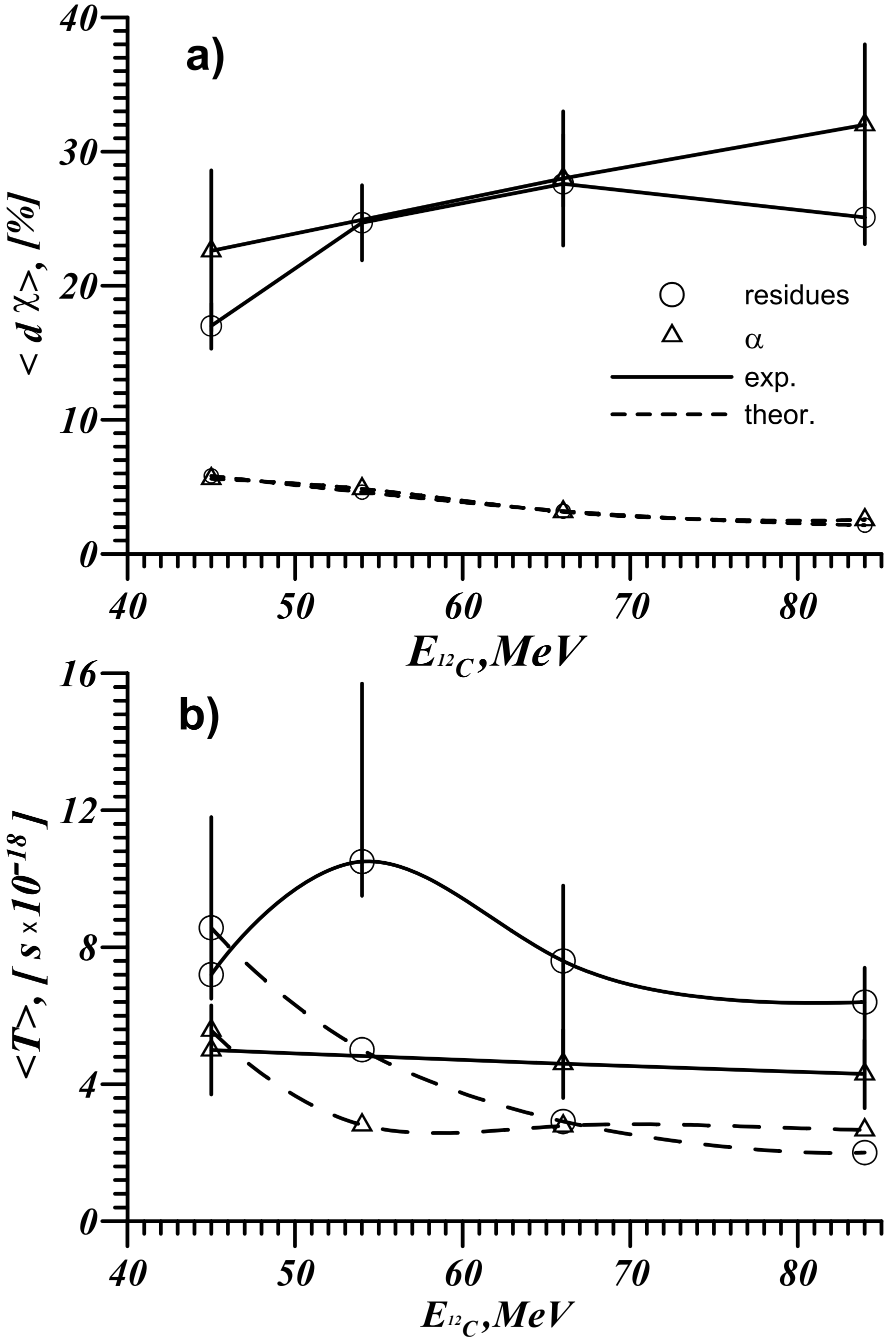
$^{12}C+^{28}Si \rightarrow ^{40}Ca$
45 МэВ
54 МэВ
66 МэВ
84 МэВ
$T_{\alpha1}$
$T_{\alpha2}$
τ, с
Θ_α



Среднее время <T> (a),

среднее смещение <S⊥> (b)

в зависимости от вида регистрируемых частиц .



Experimental results and theoretical estimations for <dχ> (fig. a) and <T> (fig b) of compound nuclei formed in the

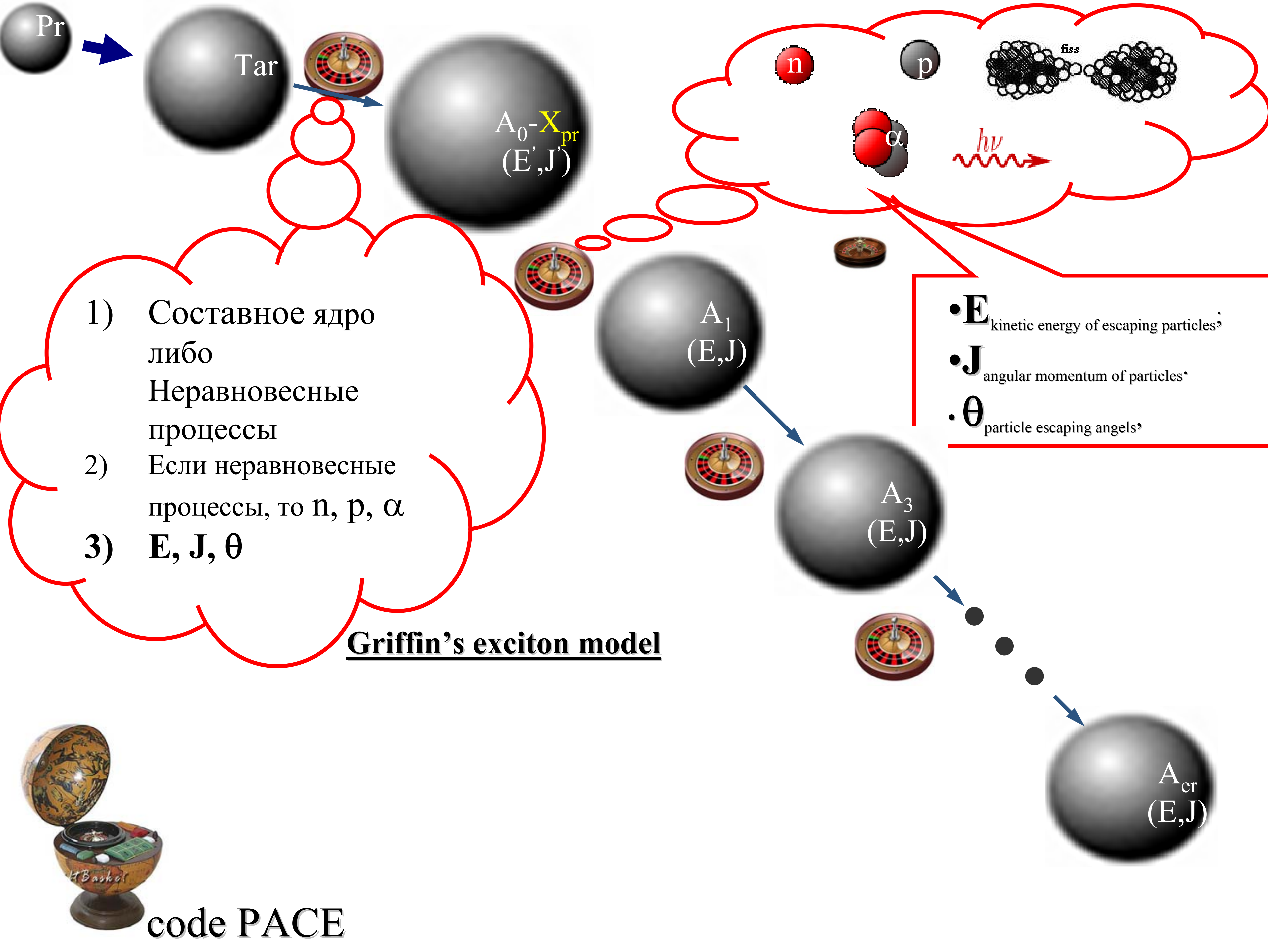
$^{12}C + ^{28}Si \rightarrow ^{40}Ca$

fusion reaction.

These experimental data were obtained using the blocking of both

evaporation residues

and low-energy α particles



Pr
Tar
A0-Xpr
(E',J')
n
p
fiss
α
hν
A1
(E,J)
A3
(E,J)
Aer
(E,J)
•E kinetic energy of escaping particles;
•J angular momentum of particles.
• θ particle escaping angels,
1) Составное ядро либо Неравновесные процессы
2) Если неравновесные процессы, то n, p, α
3) E, J, θ
Griffin's exciton model
code PACE

Краткое описание моделей

In the Griffin's exciton model of nuclear reactions, relaxation of the compound to equilibrium is described by the master equation:

метод A

$$\frac{d}{dt}q(n,t)=\sum_{m=n-2}^{m=n+2}\lambda_{m\to n}q(m,t)-q(n,t)\left(w(n)+\sum_{m=n-2}^{m=n+2}\lambda_{n\to m}\right), \quad (1)$$

метод B

The generalized master equation takes form :

$$\frac{d}{dt}q(n,\Omega,t)=\sum_{m=n-2}^{m=n+2}\lambda_{m\to n}\int d\Omega' G(\Omega,\Omega')q(m,\Omega',t)-q(n,\Omega,t)\left(w(n)+\sum_{m=n-2}^{m=n+2}\lambda_{n\to m}\right), \quad (2)$$

$$G(\Omega,\Omega')=\frac{d\sigma^f}{d\Omega'}\left(\int d\Omega'\frac{d\sigma^f}{d\Omega'}\right)^{-1} \quad (3)$$

dσ/dΩ is the free differential nucleon-nucleon scattering cross section

The initial condition for this equation is (where H is the Heavyside function)

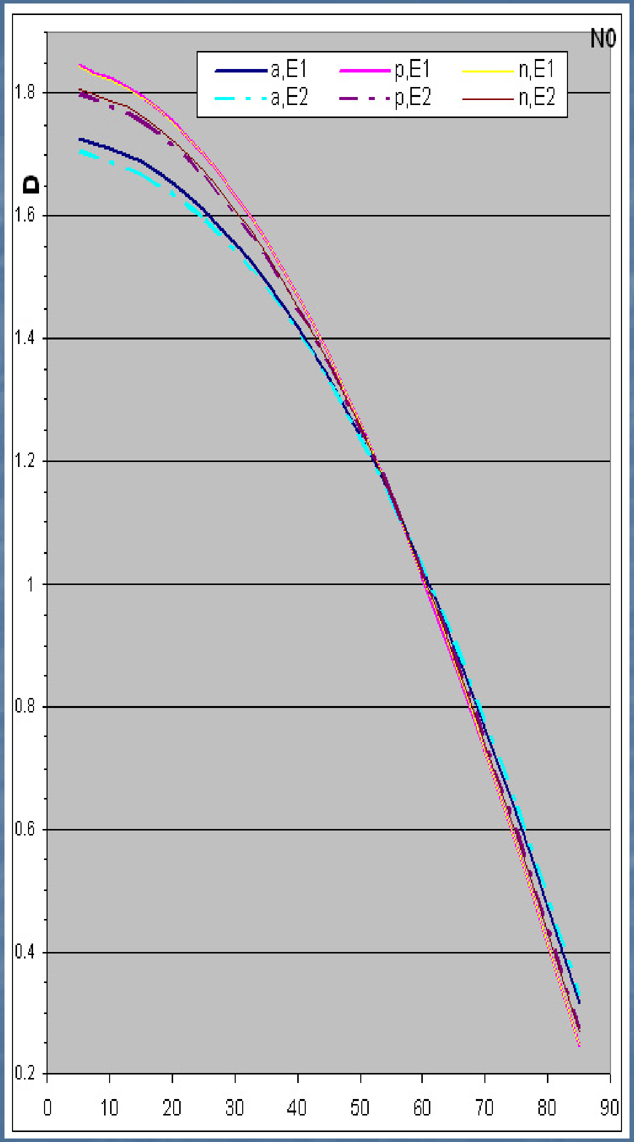
$$q(n,\Omega,t=0)=N\delta_{n,n_0}\pi^{-1}\cos(\beta\theta_{lab})H(\pi/2-\beta\theta_{lab}), \quad (4)$$

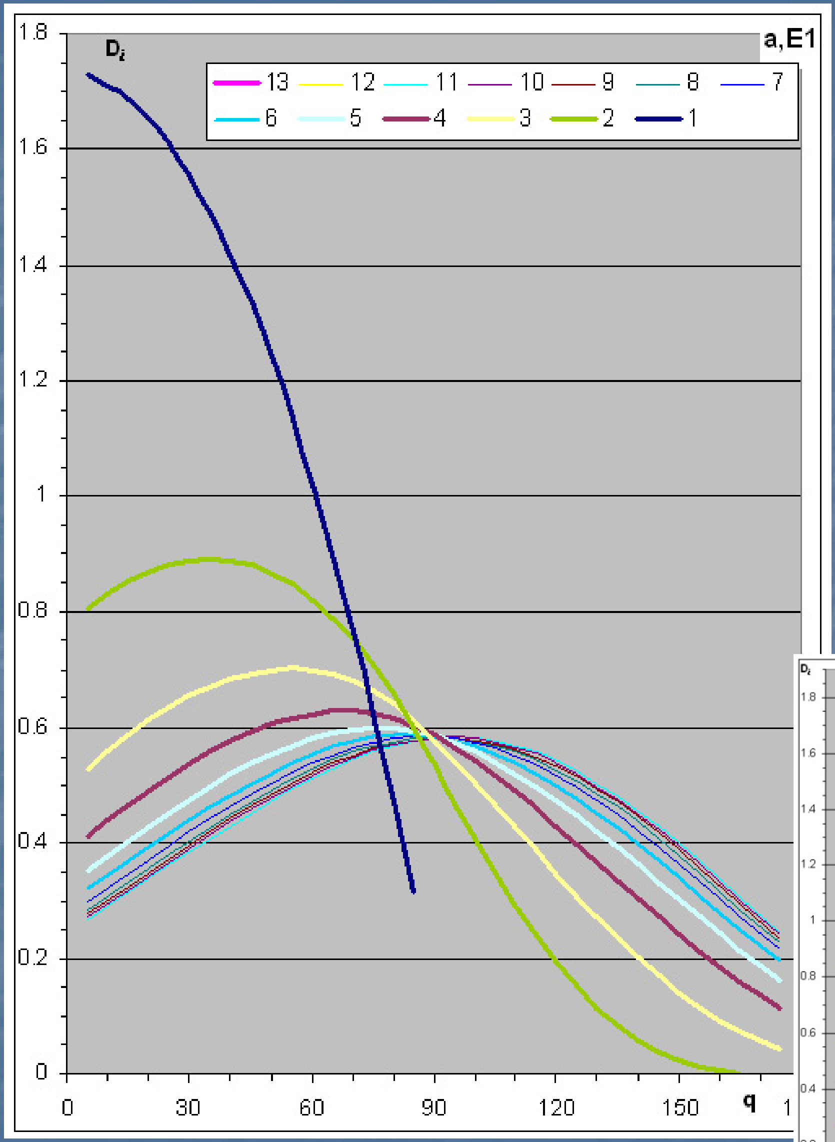
where $\beta=\frac{\pi}{4\theta_{max}}$, and $\theta_{max}=2\pi/(kR)$.

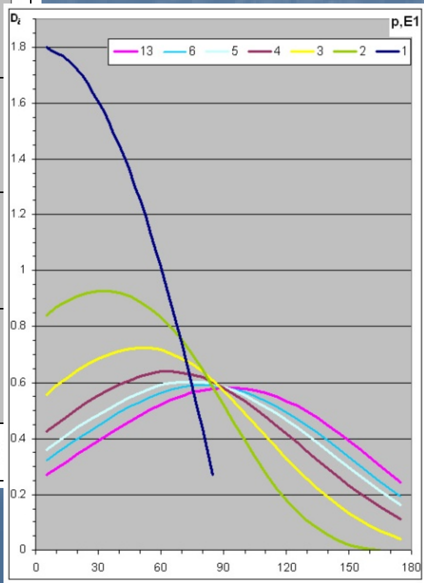
k is the incident nucleon momentum and R is the nuclear radius.

Illustration

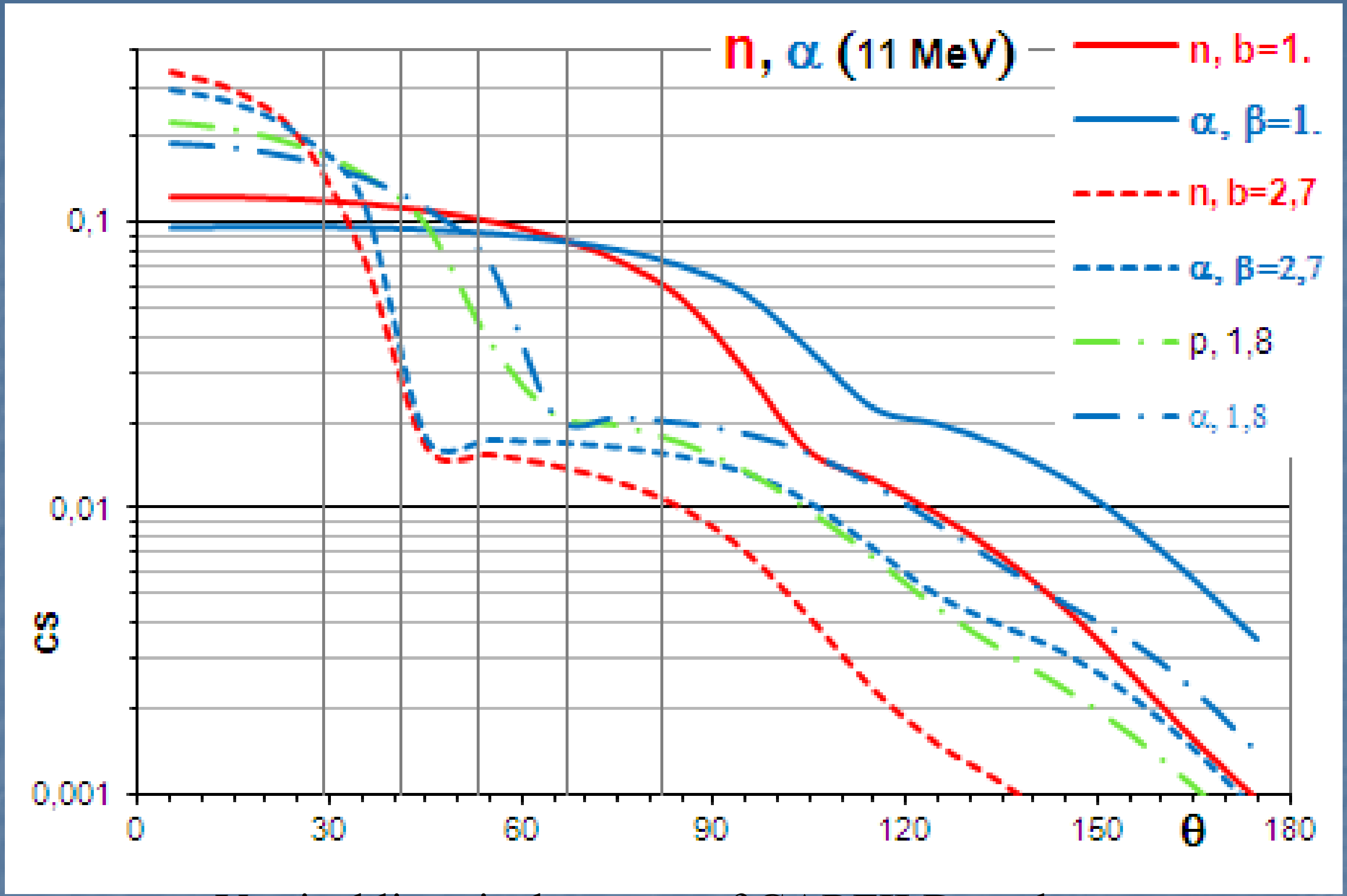
β=1.







β parameter *What affect this value? (Case B)*



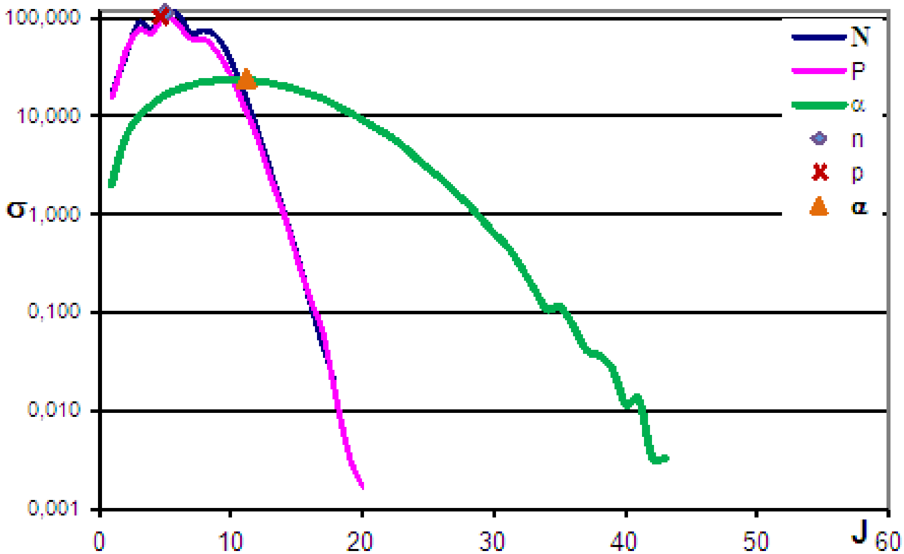
Vertical lines is the range of GARFILD angles

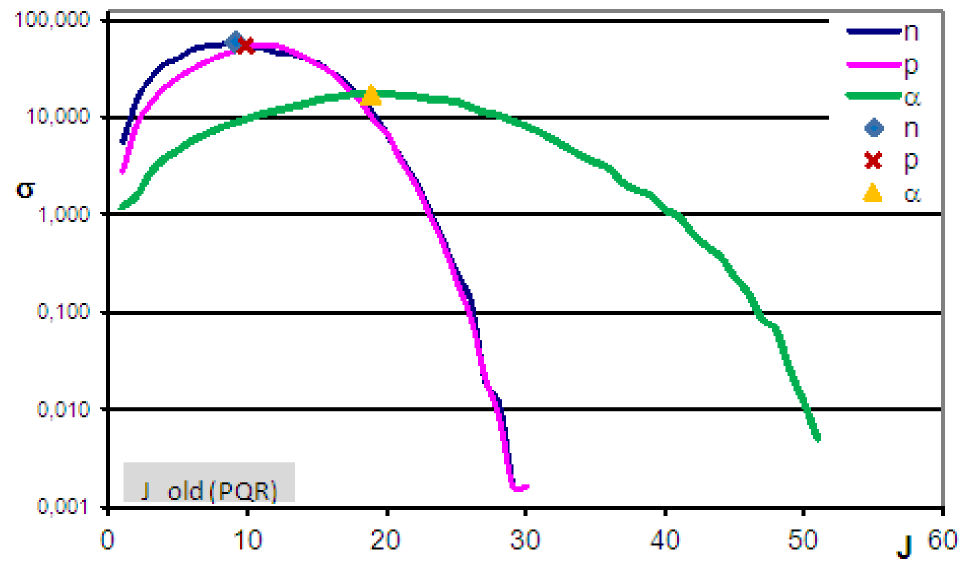
$$q(n,\Omega,t=0)=N\delta_{n,n_0}\pi^{-1}\cos(\beta\theta_{lab})H(\pi/2-\beta\theta_{lab})$$

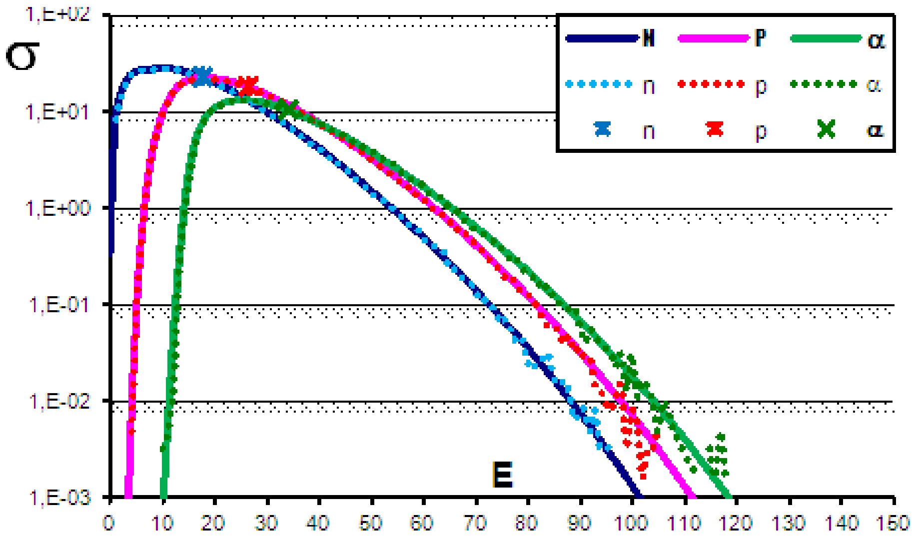
$$\beta=\frac{\pi}{4\theta_{max}},\ \theta_{max}=2\pi/(kR).$$

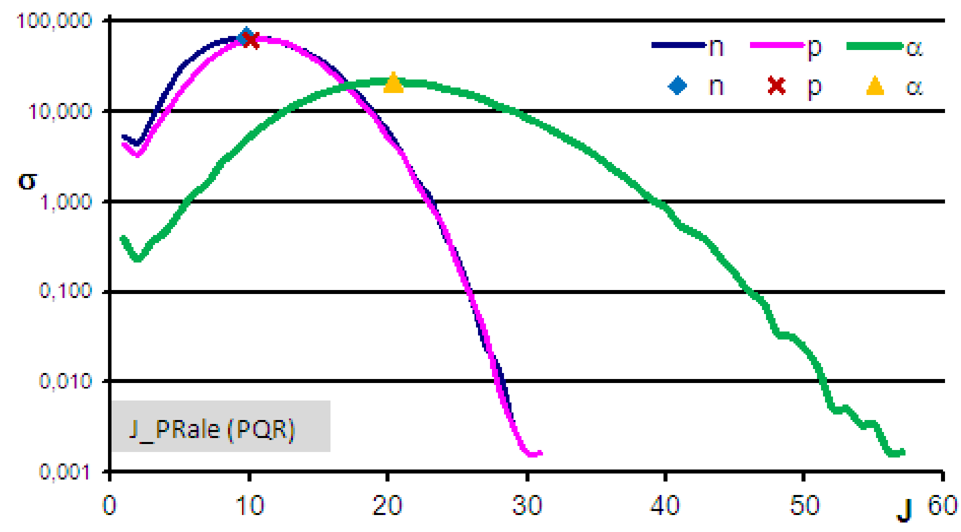
β parameter is a strong parameter !!

Case A (angular dependency by optic. model)



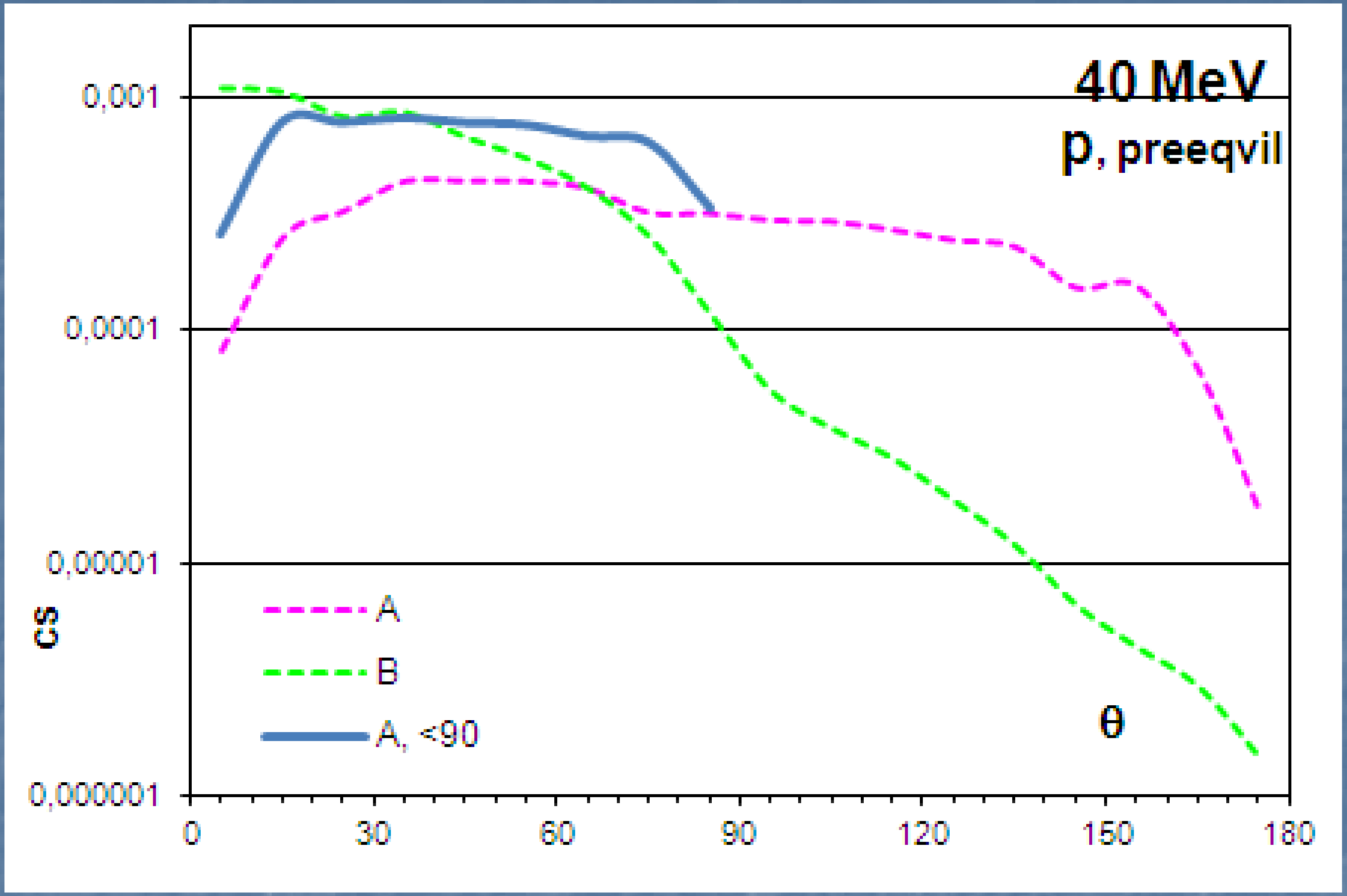




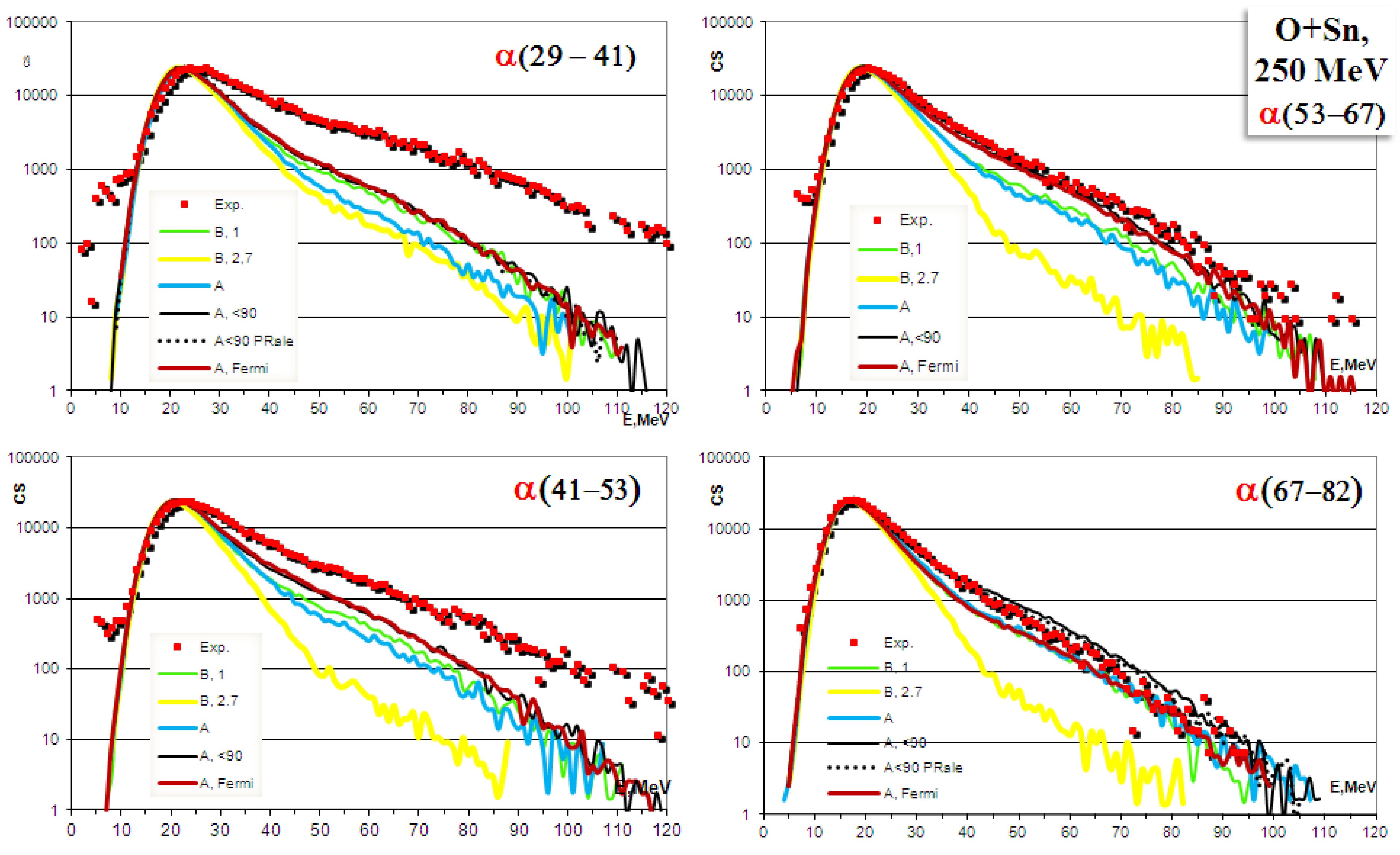


***Сечение выхода p** в лс (в относительных единицах)*

(метод А)

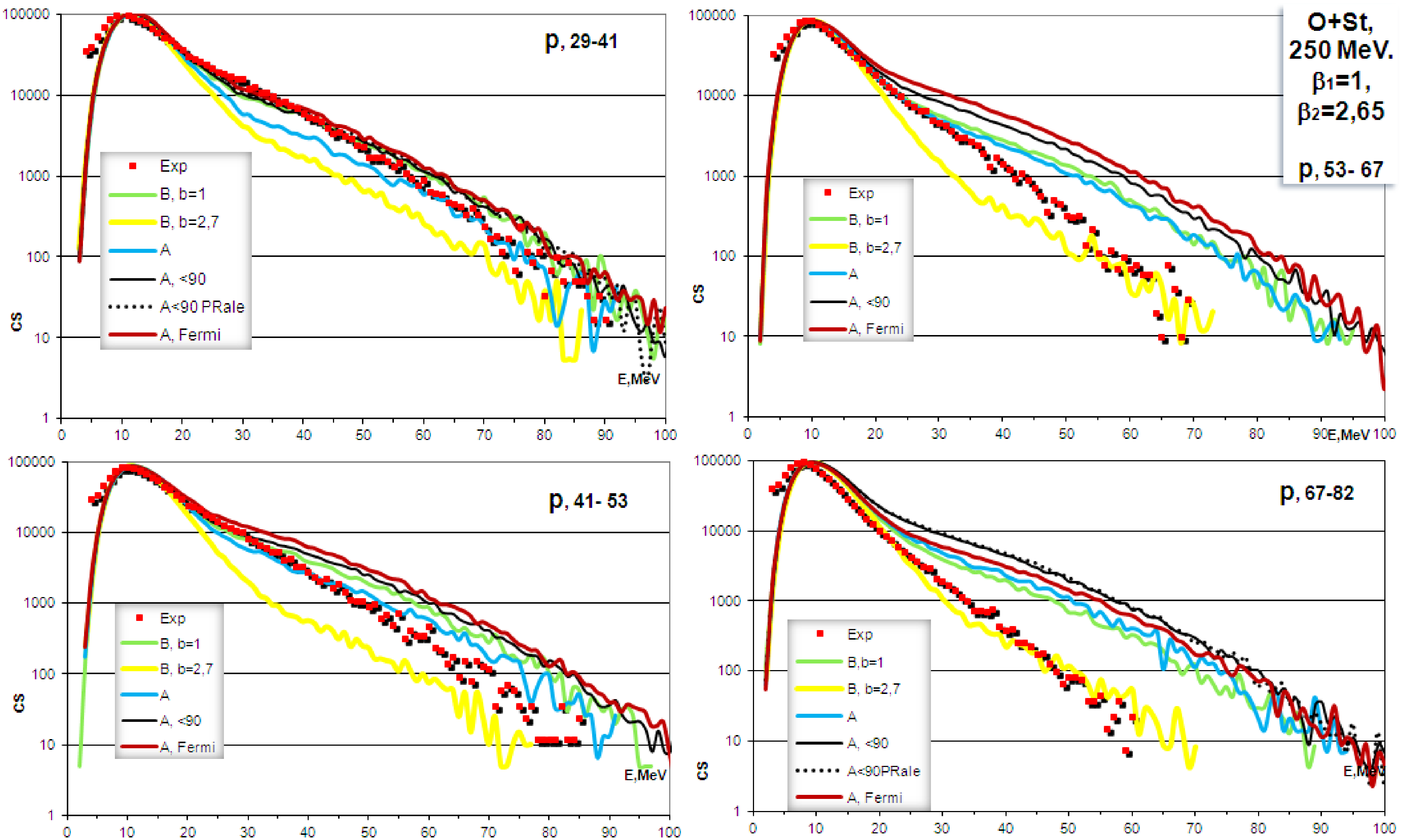


Result for α

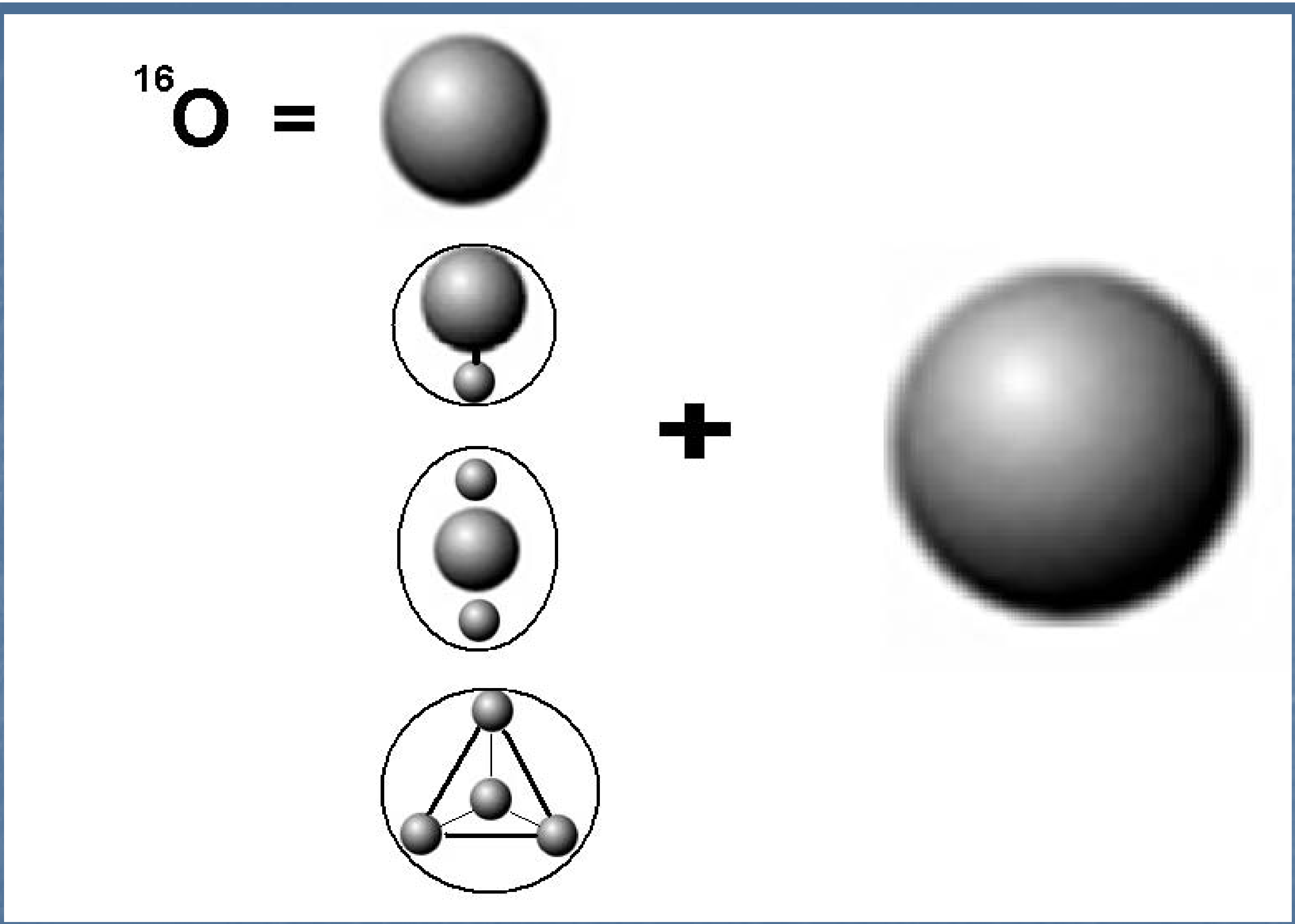


O+Sn,
250 MeV
α(53–67)
α(29 – 41)
α(41–53)
α(67–82)
Exp.
B, 1
B, 2,7
A
A, <90
A<90 PRele
A, Fermi
cs
E,MeV

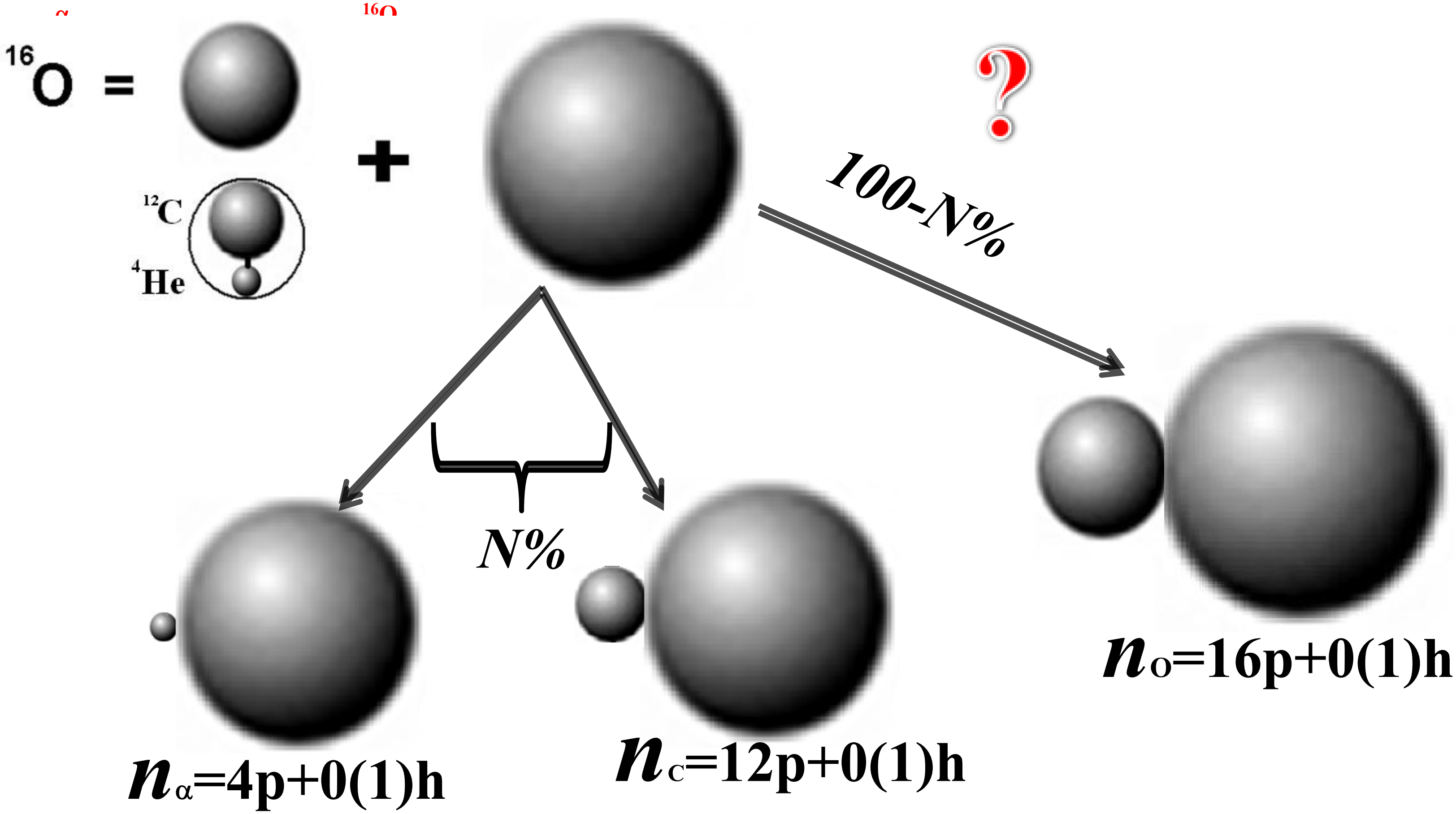
Result for p


O+St,
250 MeV.
β1=1,
β2=2,65
p, 29-41
p, 53- 67
p, 41- 53
p, 67-82
Exp
B, b=1
B, b=2,7
A
A, <90
A<90 PRale
A, Fermi
CS
E,MeV
100000
10000
1000
100
10
1
0
10
20
30
40
50
60
70
80
90
100

Possible α clustering configurations in ^{16}O nucleus



B.Buck, C.B.Dover,J.P.Vary, Phys.Rev.C, 11, 1803 (1975)
B.Buck, A.C.Merchant, S.M.Perez, Phys.Rev.C, 45, 2247 (1992)
Yu.A.Berezhnoy, V.P.Mikhailyuk.Phys.Elem.Part and Nucl., 39, 437, (2008)



If ***En***$_O$=**250MeV, then E*n*$_\alpha$+ E*n*$_C$=(250–B$_\alpha$– E$_{Clas}$)MeV**

but E*n*$_\alpha$ – ? and E*n*$_C$ – ?

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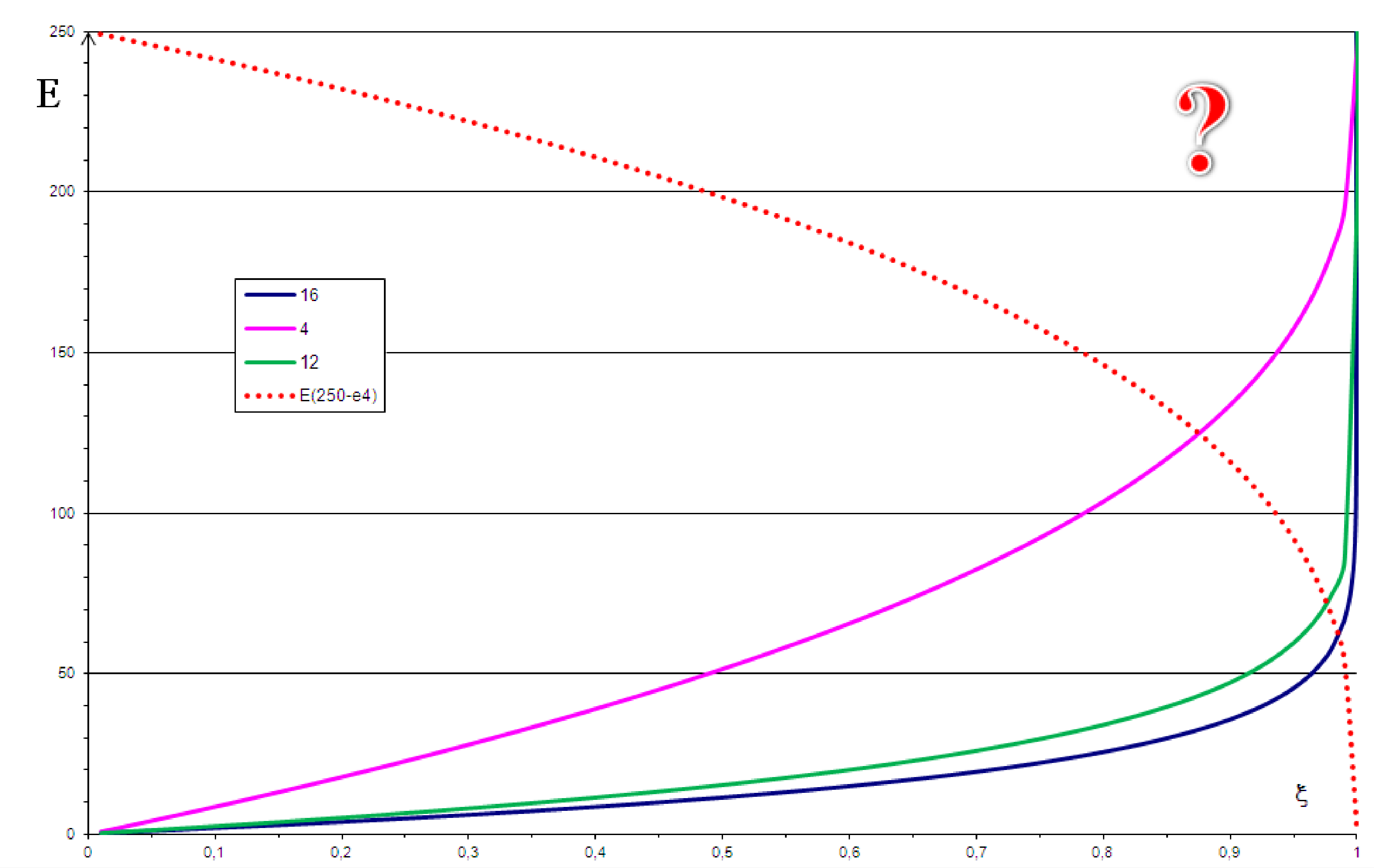
Precompound Monte-Carlo model for cluster induced reactions

M. Blann[1] and M. B. Chadwick[2]

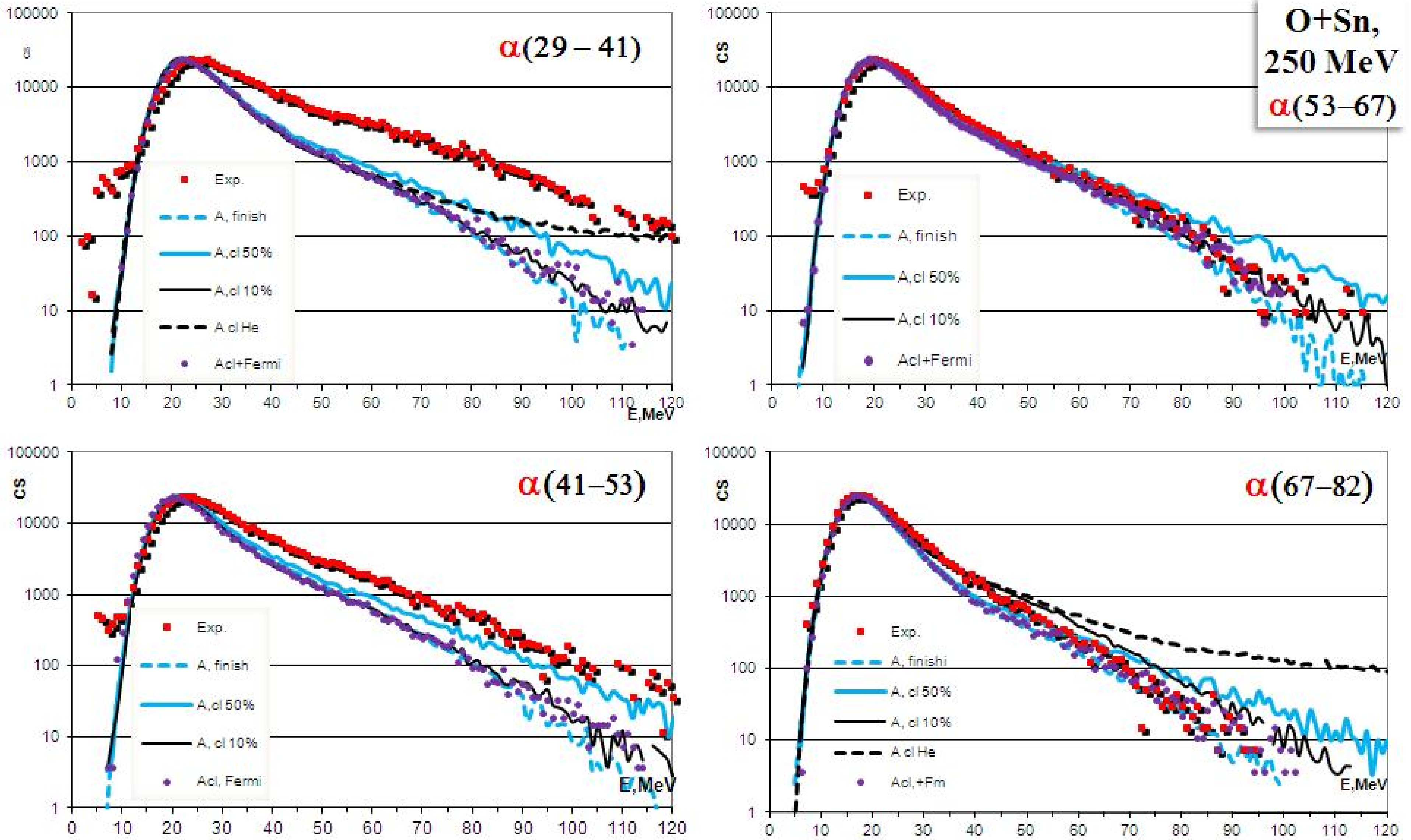
Blann model (2000)

$$e = E\left(1 - (1 - x)^{1/(n-1)}\right).$$

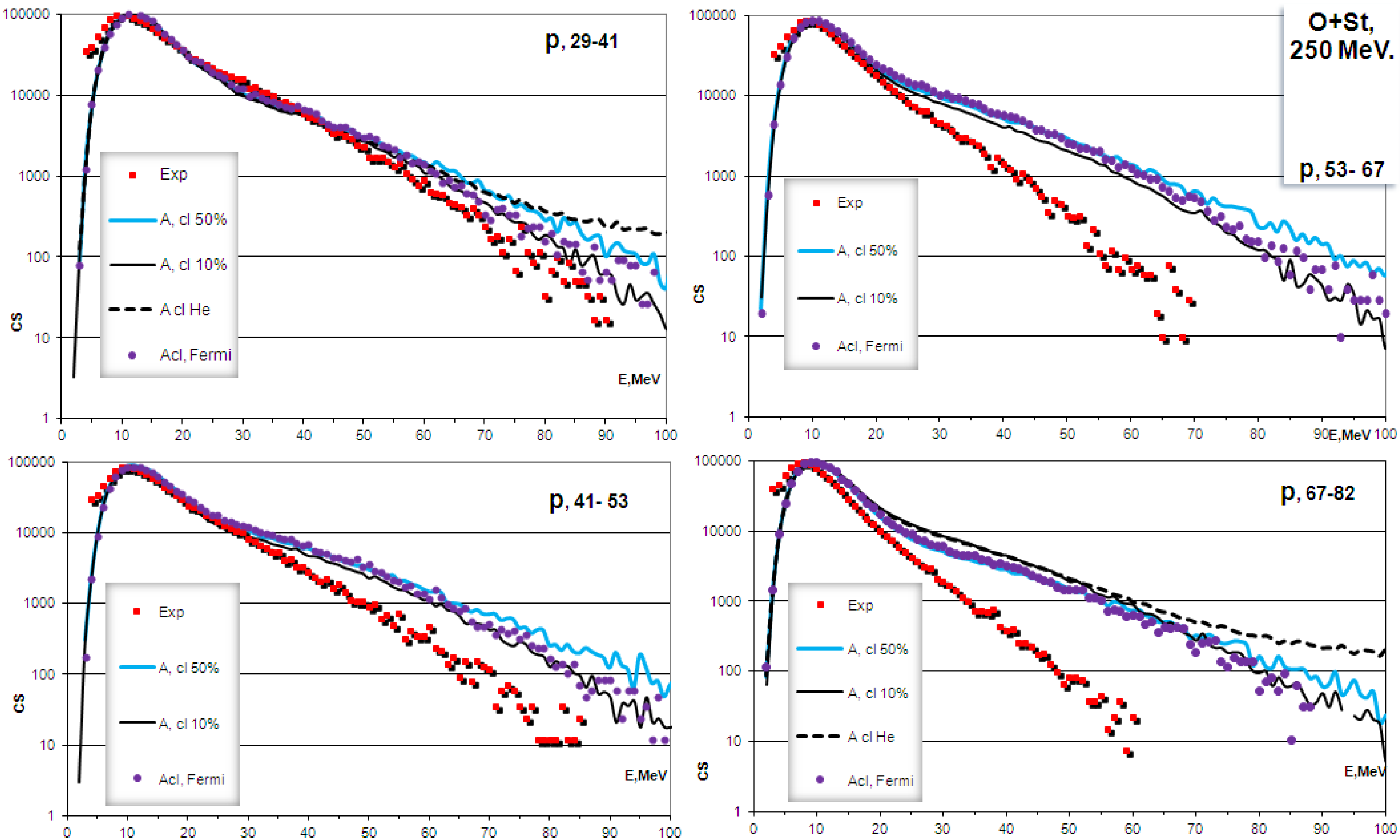
e – clusters energy, and x – random number



Preliminary Result for α

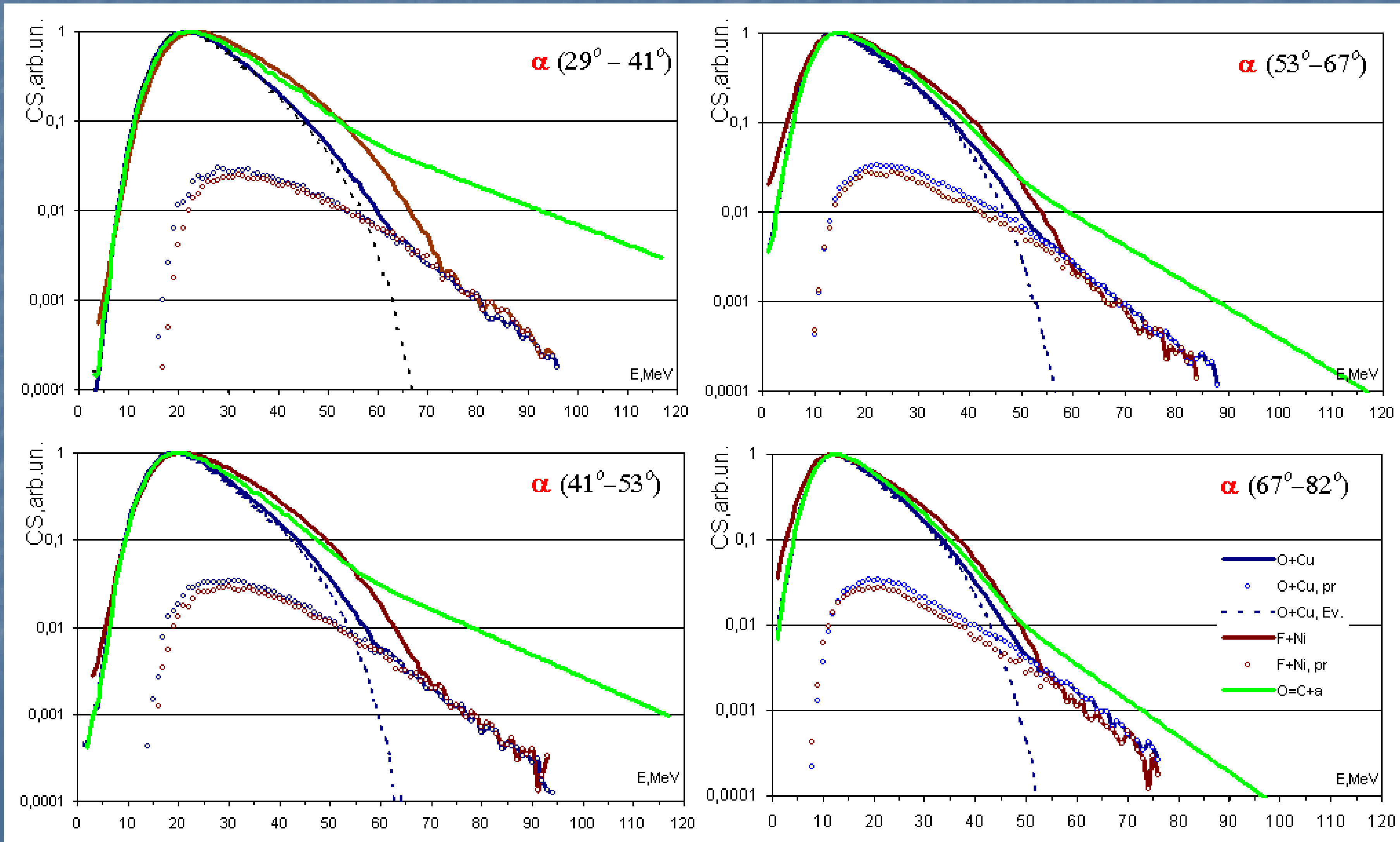


Preliminary Result for p



α,

$^{16}O+^{65}Cu \rightarrow ^{81}Rb$, E_O=240 MeV (15 MeV/u); E*=196,0MeV
$^{19}F+^{62}Ni \rightarrow ^{81}Rb$, E_F=285 MeV (15 MeV/u); E*=225,4MeV
(in lab)

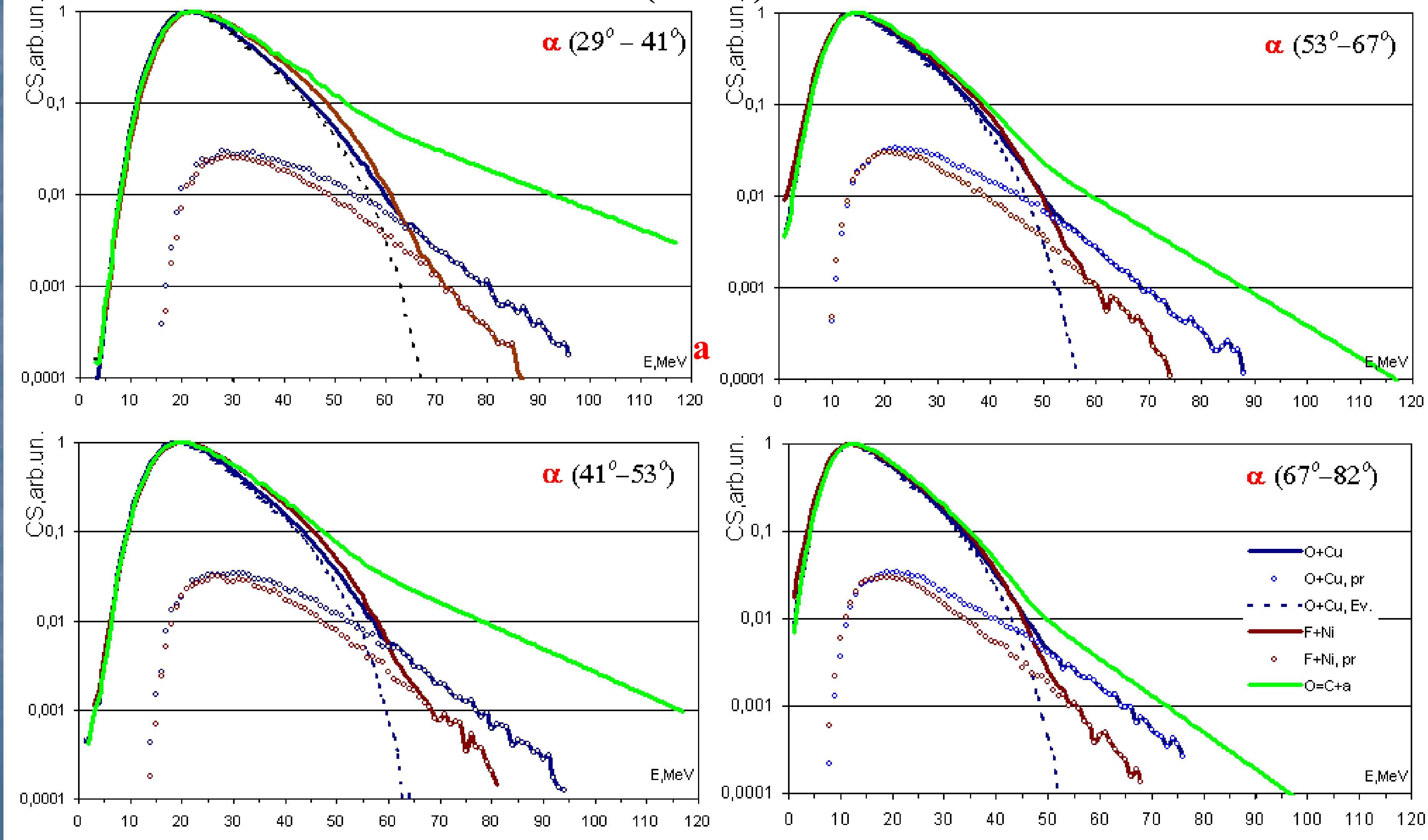


α,

$^{16}O+^{65}Cu \rightarrow ^{81}Rb$, E_O=240 MeV (15 MeV/u); E*=196,0MeV

$^{19}F+^{62}Ni \rightarrow ^{81}Rb$, E_F=247 MeV (13 MeV/u); E*=196,3MeV

(in lab)



Спасибо за внимание

Experimental setup

REACTIONS

15 MeV/u (240 MeV) $^{16}O+^{65}Cu \rightarrow ^{81}Rb^*$ E*=196.0 MeV

13 MeV/u (247 MeV) $^{19}F+^{62}Ni \rightarrow ^{81}Rb^*$ E*=196.3 MeV

OR

15 MeV/u (240 MeV) $^{16}O+^{65}Cu \rightarrow ^{81}Rb^*$ E*=196.0 MeV

15 MeV/u (285 MeV) $^{19}F+^{62}Ni \rightarrow ^{81}Rb^*$ E*=225.4 MeV

BEAMS

Pulsed 1pnA ^{16}O and ^{19}F beams

Estimated time: 3 days for each reaction + 1 day for calibration

SETUP

GARFIELD Camera Forward (for LCP evap+pre-eq)

+

[GARFIELD Camera Backward (for LCP evap)]

+

RING or PHOS or PPAC (for ER)

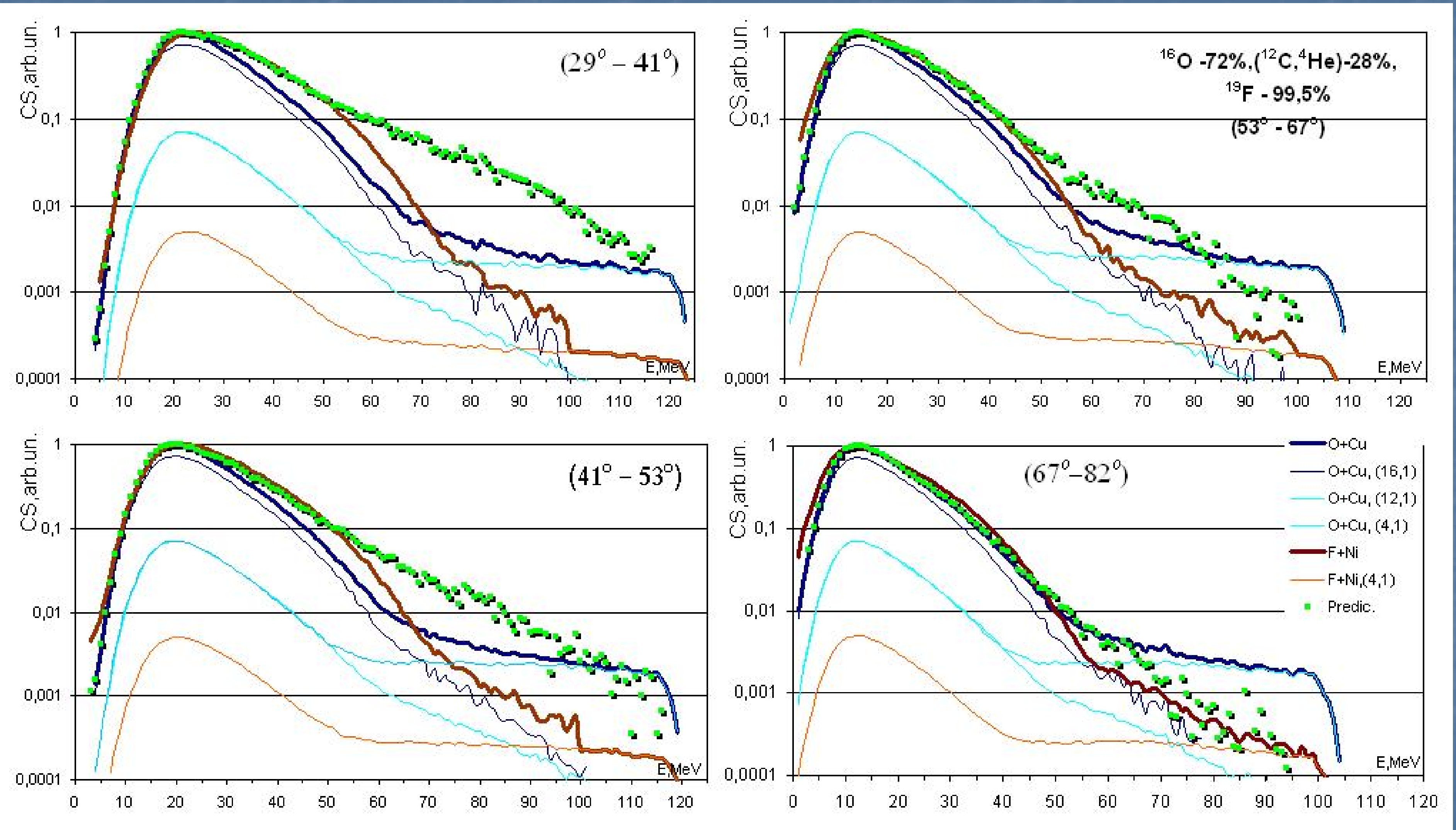
IMPORTANT!

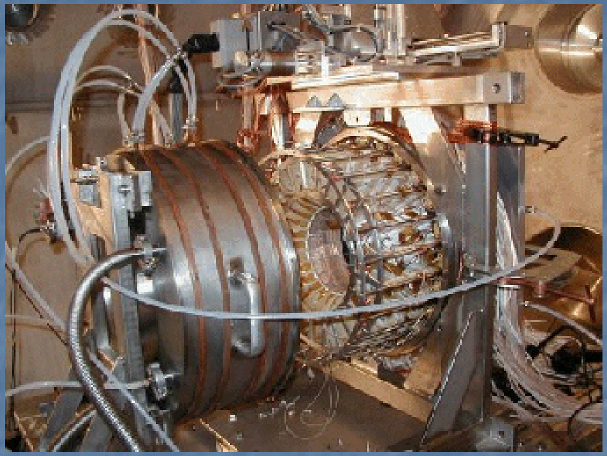
Discrimination between CF and ICF (TOF)
is absolutely necessary for this experiment

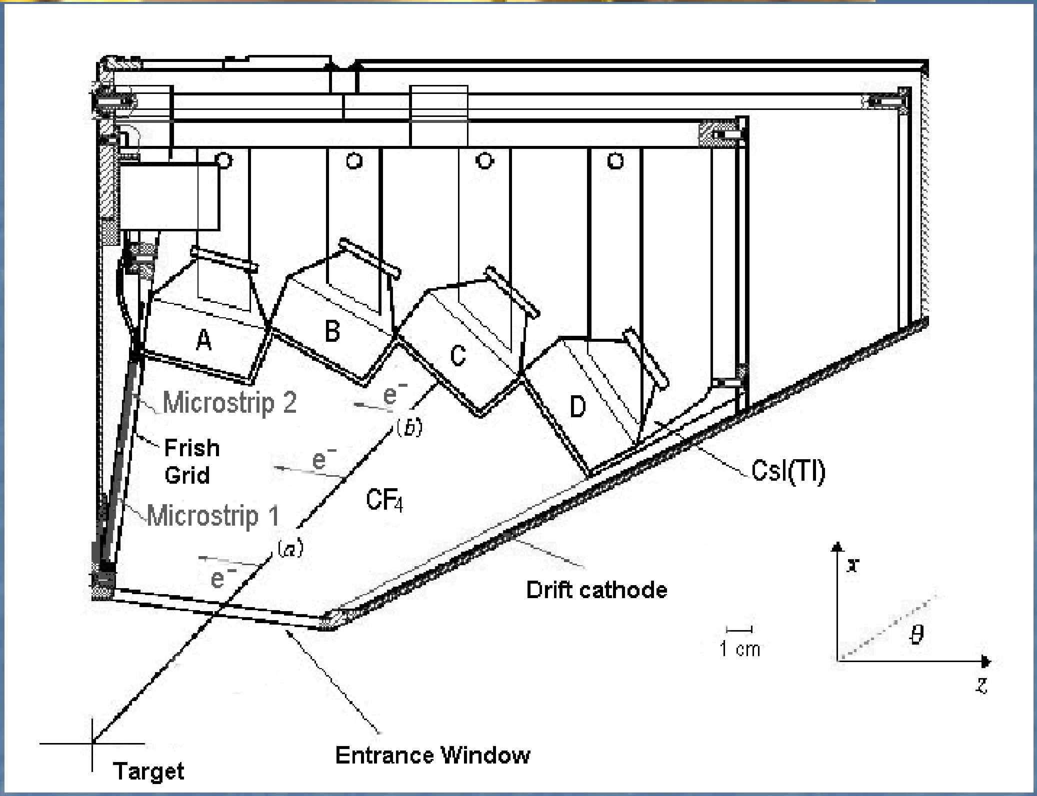
Illustration

E=15 MeV/u

$^{16}O+^{65}Cu$
$^{19}F+^{62}Ni$







GARFIELD - 4π complex multidetector apparatus for particle detection

-Double stage ΔE-E (CsI(Tl)-MSGC) telescopes

-In the experiment the angular coverage is 29°- 151° in θ and 4π in φ

-Charge resolution from Z=1 to Z=28

-Typical energy resolution for CsI(Tl) crystal is 3.0% for 5.5 MeV α

-Identification threshold is 0.9 MeV/u