Pre-equilibrium emission and its possible relation to α-clustering in nuclei

T. Marchi
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INFN Istituto Nazionale di Fisica Nucleare

NUCL-EX

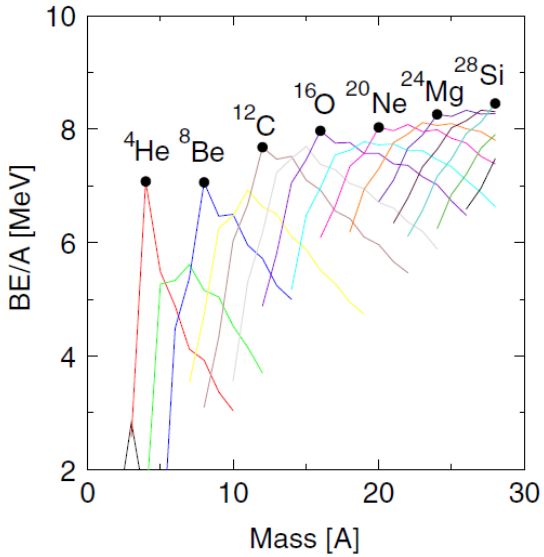
IWM-EC 2014 International Workshop on Multi facets of Eos and Clustering

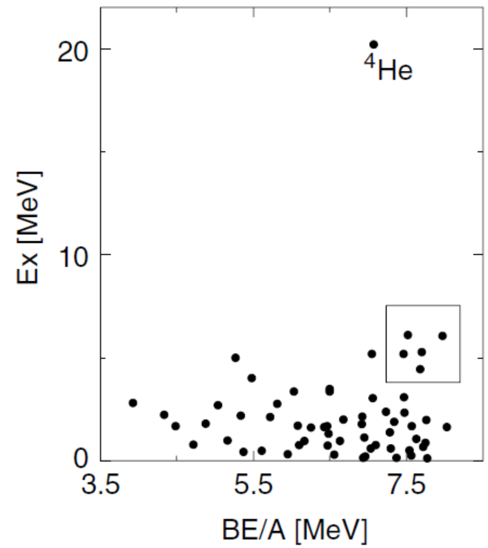
6-9 May 2014 *Dipartimento di Fisica e Astronomia and Laboratori Nazionali del Sud Catania - Italy*

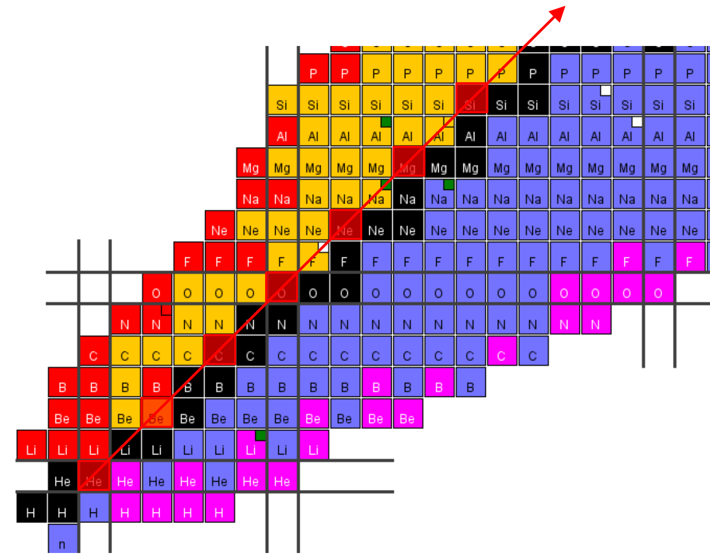
G. AR. F. I. E. L. D.
General ARray for Fragment Identification and for Emitted Light particles in Dissipative Collisions

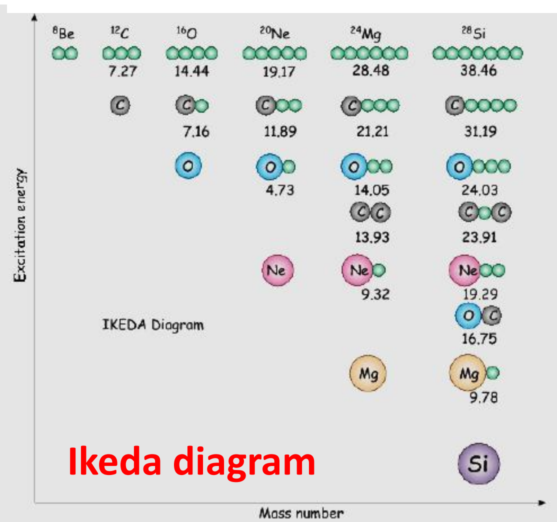
α-clusters in light nuclei:

In 1968 Ikeda suggested that α-conjugate nuclei are observed as excited states close to decay threshold into clusters. The original idea was introduced by Hafstad and Teller in 1938.
The starting point is a quite reasonable observation:



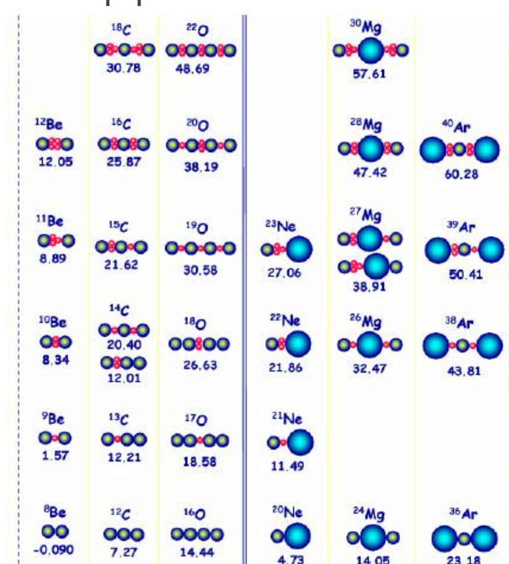






Cluster structure appears close to the decay thresholds

The interest in nuclear clustering has been pushed strongly due to the study of **neutron-rich and exotic weakly-bound nuclei**



W. Von Oertzen et al., Phys. Rep. 432 (2006) 43
M. Freer et al., Rep. Progr. Phys. 70 (2007) 2149
Ebran et al., Nature 487 (2012) 341

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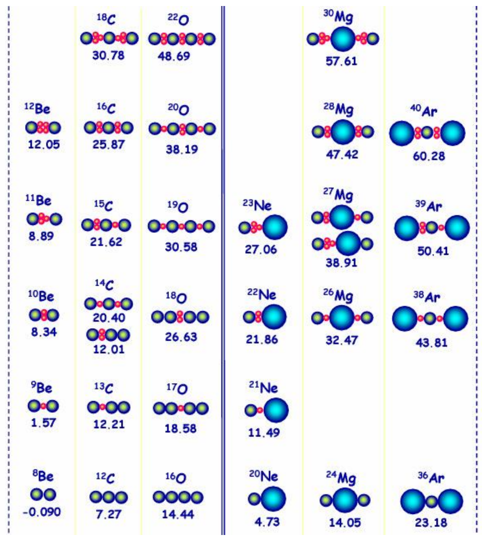
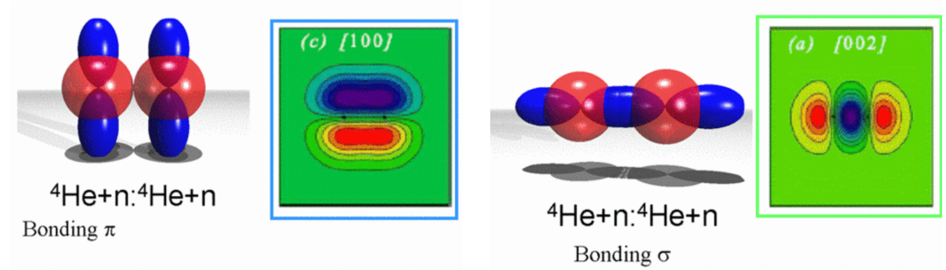
Extension of the clustering concepts

In light nuclei at the neutron drip-line, clustering might be the preferred structural mode

Nuclear states built on clusters bound by valence neutrons in their molecular configurations might appear

Extended Ikeda diagrams





Presently these structures are mainly described by theory, but must be experimentally verified at the new radioactive beam facilities

WHAT ABOUT HEAVY NUCLEI?

Cluster emission, transfer and capture in nuclear reactions

P.E. Hodgson[a], E. Běták[b,1]

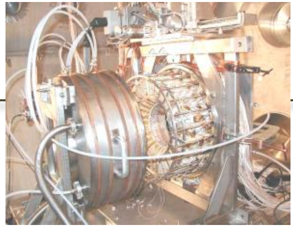
Physics Reports 374 (2003) 1–89

1. Pre-equilibrium processes
2. Coalescence vs Preformation

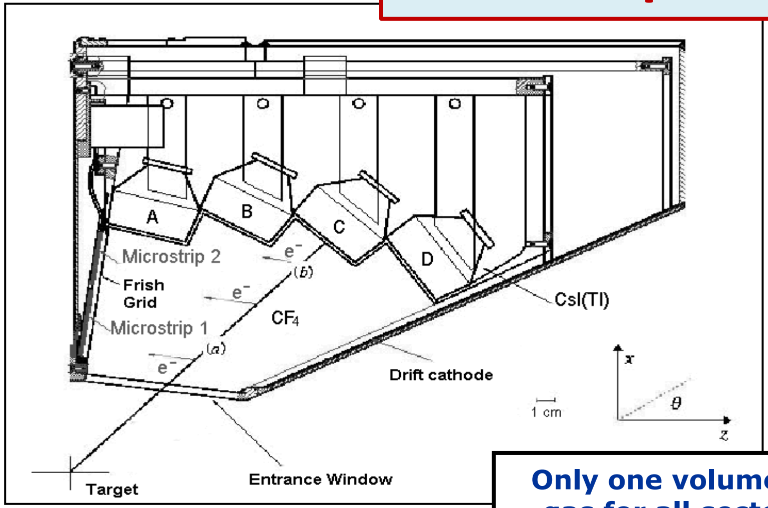
Shopping list…

	E_beam		η	Comp	E*	Detectors
^{16}O + ^{116}Sn	130 MeV 250 MeV	8 AMeV 15.8 AMeV	0.76	^{132}Ce	100 206	GARF FW+ PPAC
^{16}O+^{116}Sn	192 MeV	12 AMeV	0.76	^{132}Ce	155	GARF FW+ PHOSWICH
^{16}O+^{65}Cu	256 MeV	16 AMeV	0.60	^{81}Rb	209	GARF FW+BW+ RCo
^{19}F + ^{62}Ni	304 MeV	16AMeV	0.53	^{81}Rb	240	GARF FW+BW+ RCo
^{19}F + ^{63}Cu	304 MeV	16 AMeV	0.52	^{82}Sr	243	GARF FW+BW+ RCo

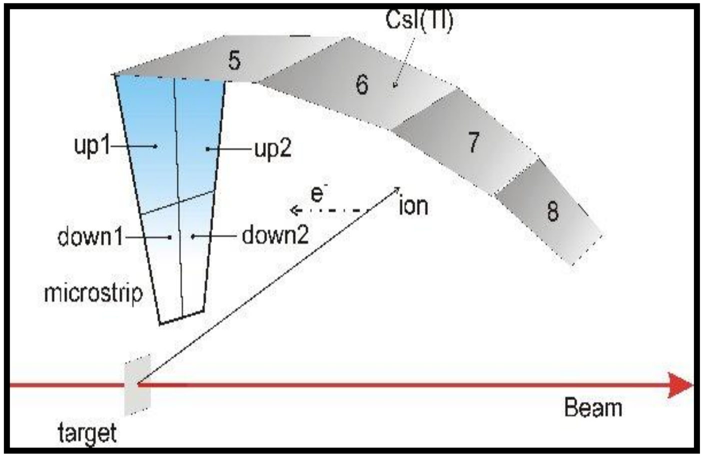
Experimental setup: GARFILED + …



Microstrip Drift Chamber + CsI(Tl)



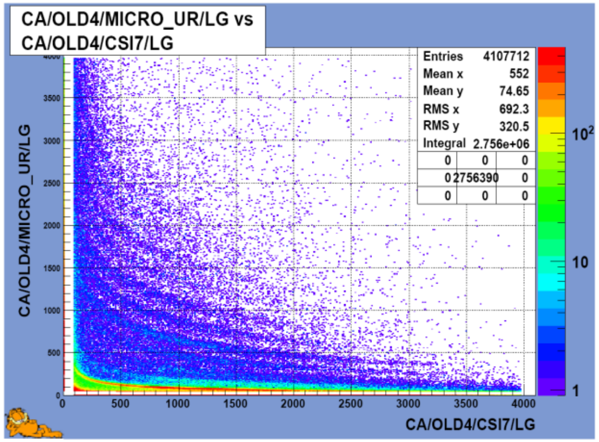
Only one volume of gas for all sectors



Double stage **ΔE-E: Micro Strip Gas Counter (MSGC)+ CsI(Tl) telescopes**
(in total **180+180** for the 2 chambers)

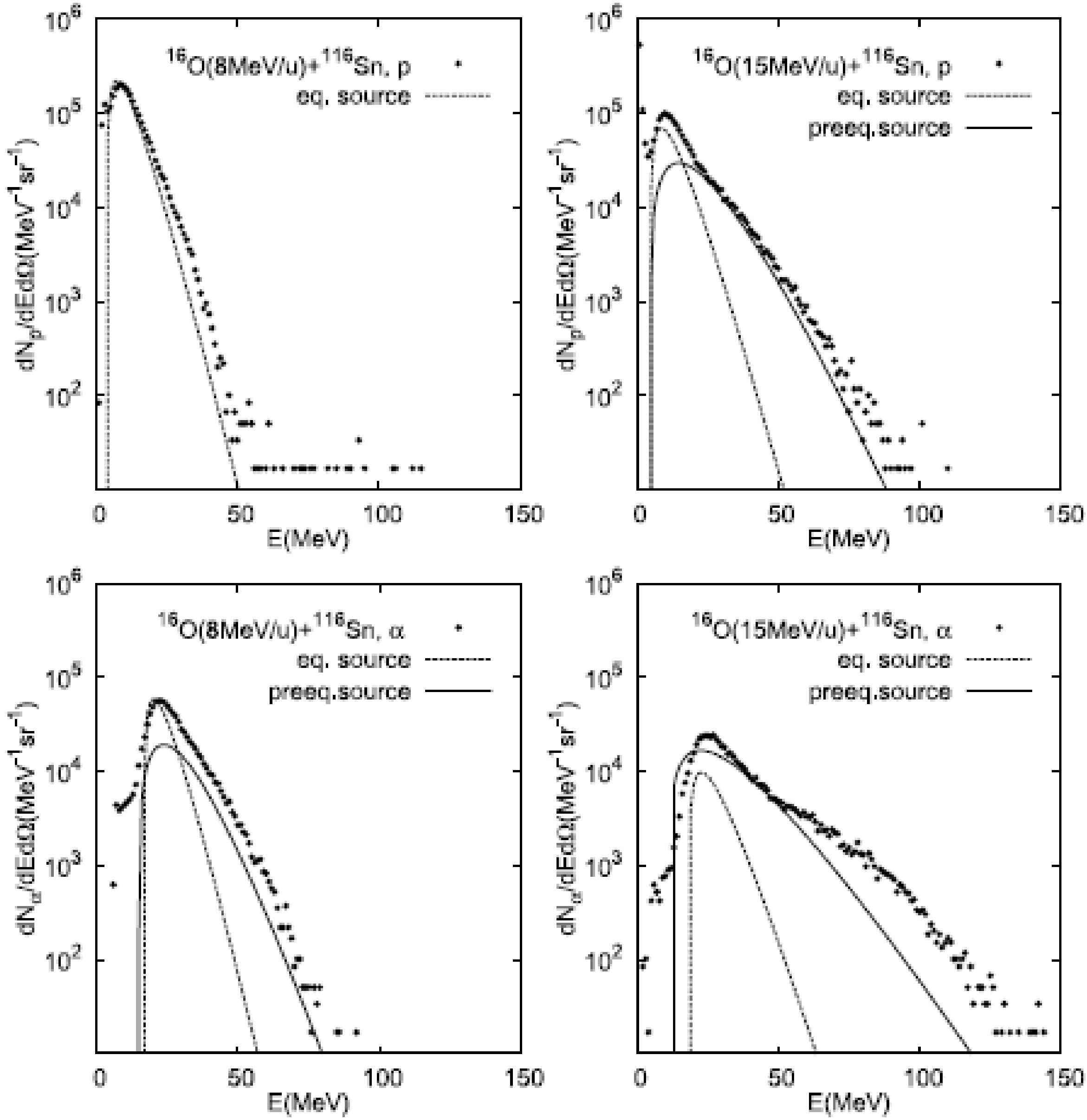
Forward Chamber
29°<θ<83°
0°< ϕ<70°
110°< ϕ<360°

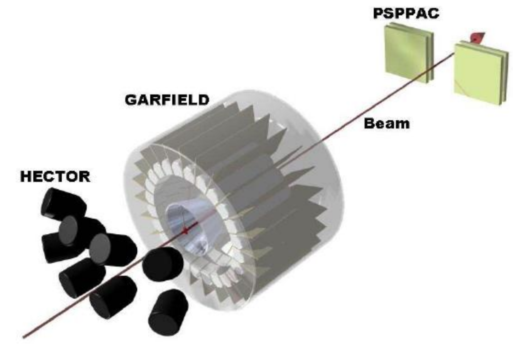
Backward Chamber
97°<θ<151°
0°<ϕ<360°



F. Gramegna et al., IEEE Nucl. Sci. Symp. Conf. Proc. 2, 1132 (2004)
A.Moroni et al. NIM A556 (2006) 516
M. Bruno et al., EPJ A 49 (2013) 128

Experimental results (2002-2003): $^{16}O + ^{116}Sn$ 130,250 MeV (8, 16 AMeV)





GARFIELD FW + HECTOR + PPAC

Light charged particles in coincidence with Evaporation Residues

A. Corsi et al., PLB 679 (2009) 197

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"Our" model: statistical + pre-equilibrium emission

Evaporative (statistical) emission:

Statistical decay of a Compound Nucleus is analyzed using modified PACE2 Monte Carlo code, with level density parametrization [A.V. Ignatyuk et al. Sov. J.Nucl. Phys. 29 (1979) 450], decay competition probability (n, p, a, g or fission), kinetic energy of emitted particles, binding energy, transmission coefficients, angular momentum.

- Insertion of non-equilibrium stage in the fusion reaction
- All the process probabilities are calculated within the Hauser-Feshbach model

Pre-equilibrium emission:

The relaxation process in the nuclear system after fusion reaction is described by the Hybrid exciton model based on Griffin model [J.J.Griffin Phys. Rev. Lett.17 (1966) 478].
The state of nuclear system produced in the collision is determined by the exciton number n=p+ h, where p is the number of valence particles over the Fermi energy and h the number of holes located under the Fermi energy, and by excitation energy E*.

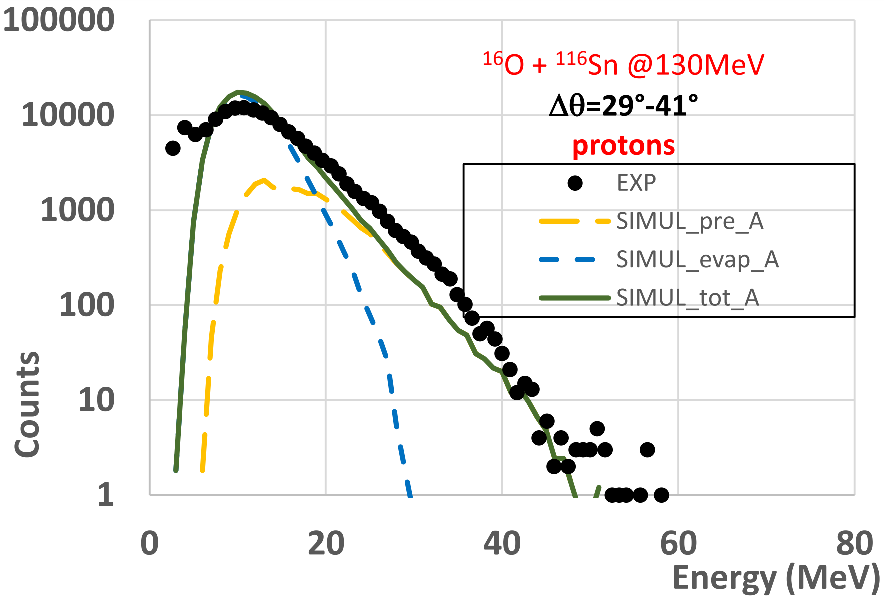
- The exciton number can be determined from the empirical trend [N.Cindro et al. Phys. Rev. Lett. 66 (1991) 868; E. Běták Fizika B12 (2003) 11]

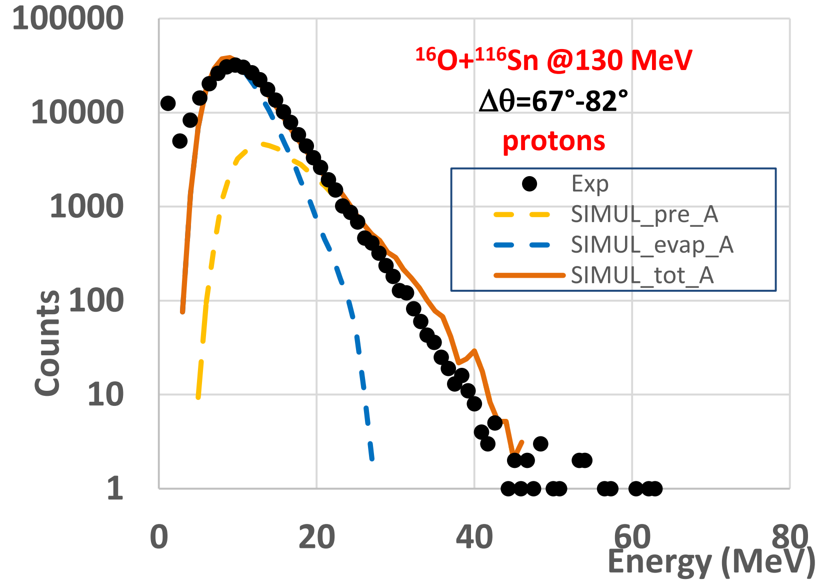
Model Parameters:

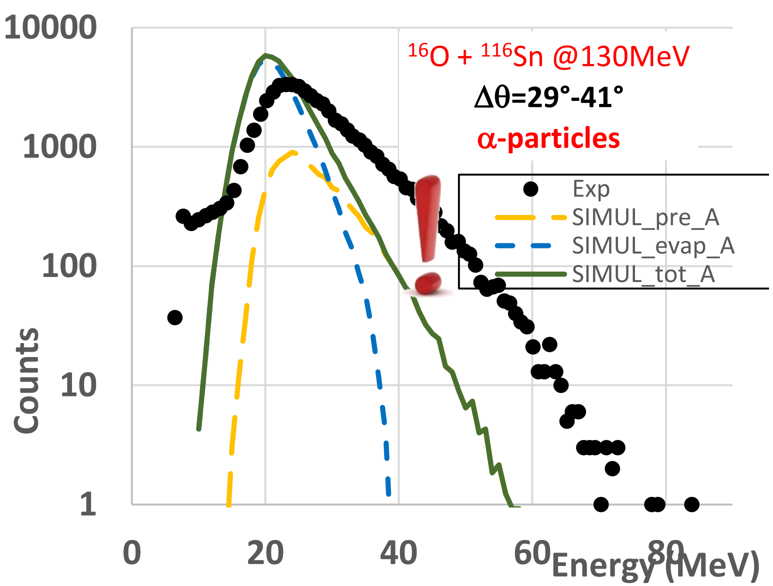
$n_0 = p_0 + h_0$	Number of excitons
k	100 – 800 MeV^3
$g = 6a/\pi^2$	Level density parameter

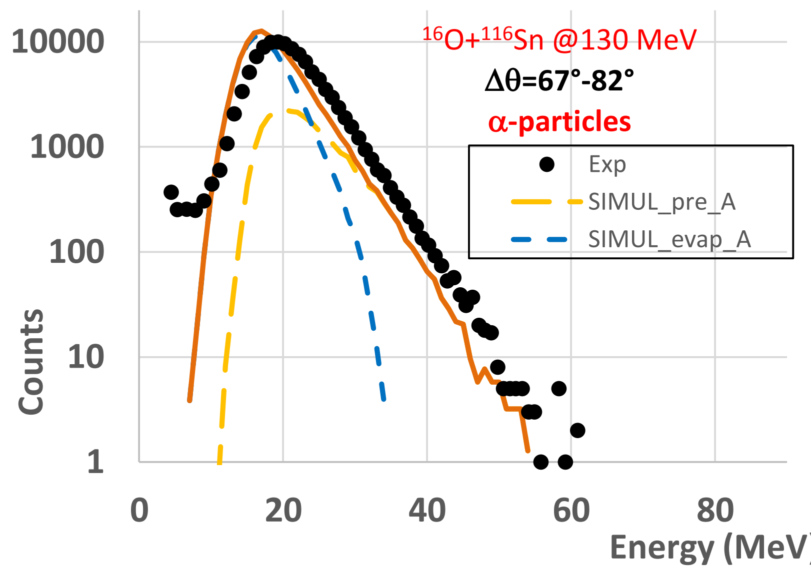
O.V. Fotina et al. Int. Journ. Mod. Phys. E19 (2010) 1134
D.O. Eremenkoet al. Phys Atom. Nucl. 65 (2002) 18
O.V. Fotina et al. Phys. Atom. Nucl. 73 (2010) 1317c

Comparison with the model (130 MeV)









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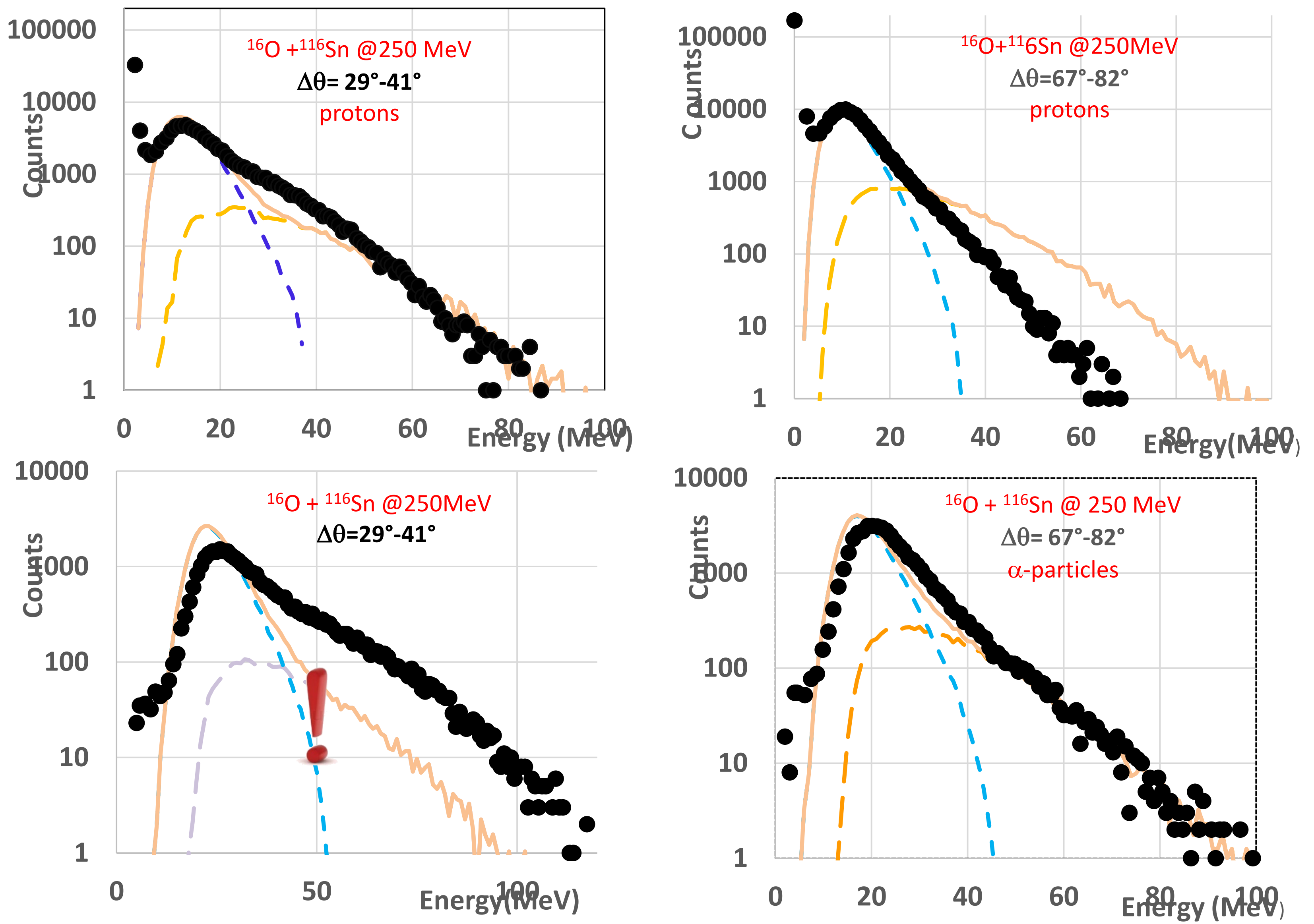
Comparison with the model (250 MeV)



“Our“ model: statistical + pre-equilibrium emission + CLUSTERING

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Statistical decay of a Compound Nucleus is analyzed using modified PACE2 Monte Carlo code , with level density parametrization [A.V. Ignatyuk et al. Sov. J.Nucl. Phys. 29 (1979) 450], decay competition probability (n, p, a, g or fission), kinetic energy of emitted particles, binding energy, transmission coefficients, angular momentum.

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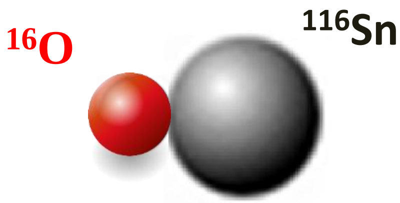
- The exciton number can be determined from the empirical trend [N.Cindro et al. Phys. Rev. Lett. 66 (1991) 868; E. Běták Fizika B12 (2003) 11]

Clustering:

Pre-formation probability of cluster and exciton energies for cluster/light ion induced reactions [M. Blann et al. Phys Rev. C 62 (2000) 034604]

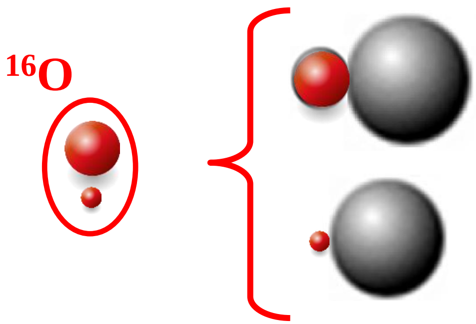
Adding α-clusters preformation probability to the decay model:

2 possible starting configurations are considered in ^{16}O nucleus



nO=16p+0(1)h

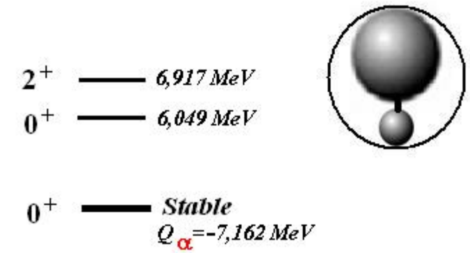
100 - N(%)

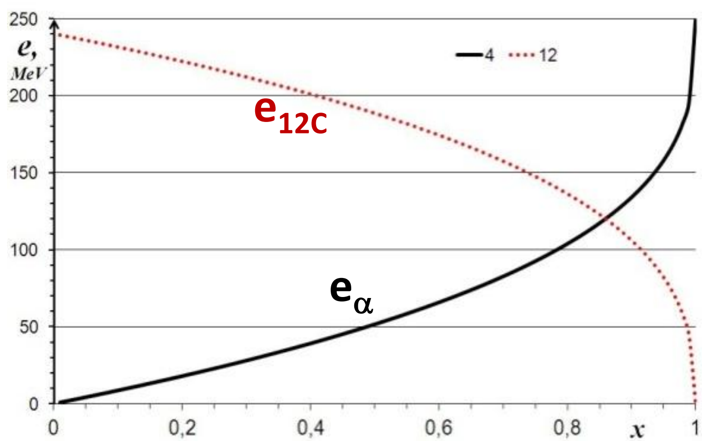


n_C=12p+0(1)h

n_α=4p+0(1)h

N(%) = ??





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

e – clusters energy

x – random number

PHYSICAL REVIEW C, VOLUME 62, 034604

Precompound Monte-Carlo model for cluster induced reactions

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

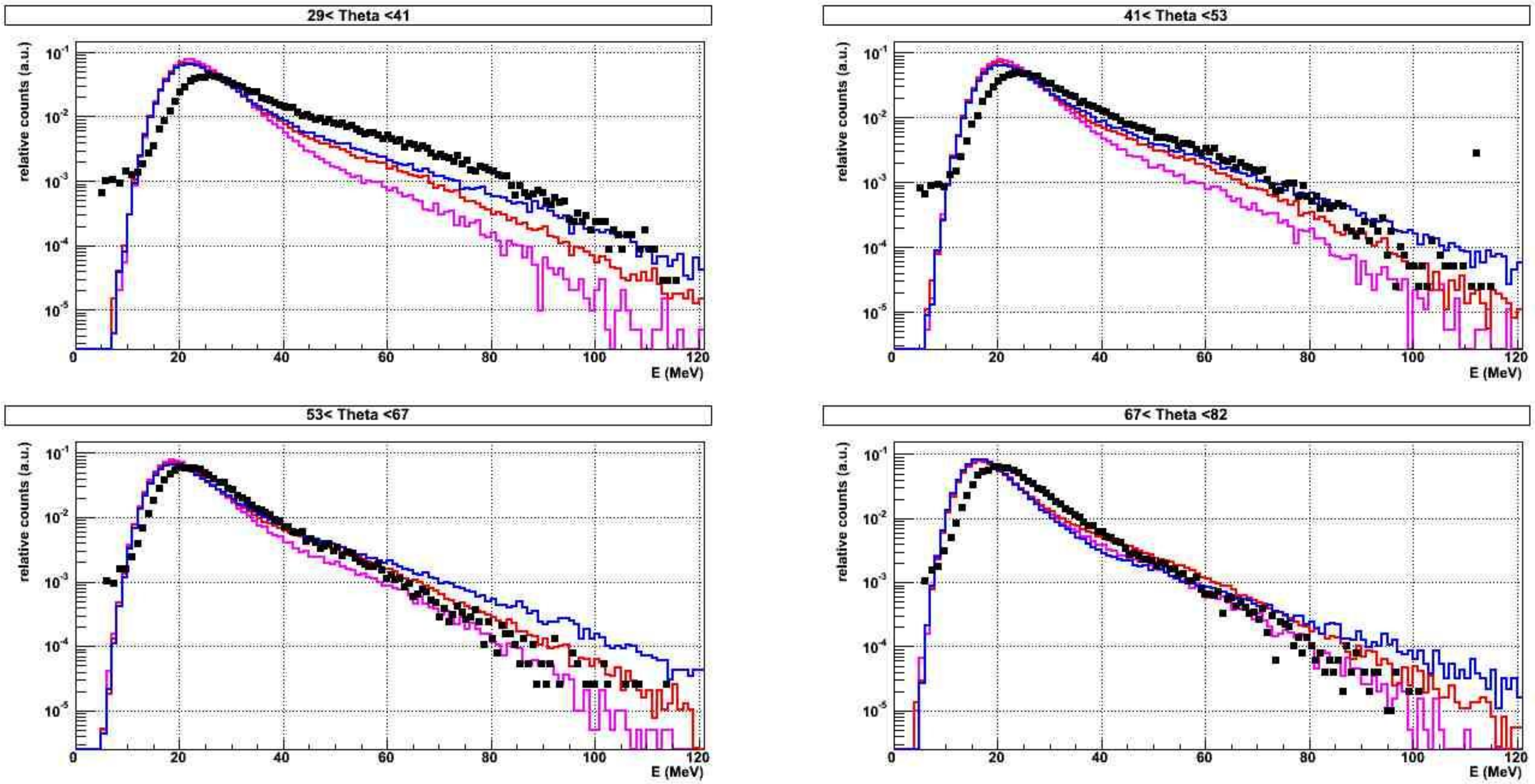
G. AR. F. I. E. L. D.

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

Experimental results (2002-2003) – with clustering:

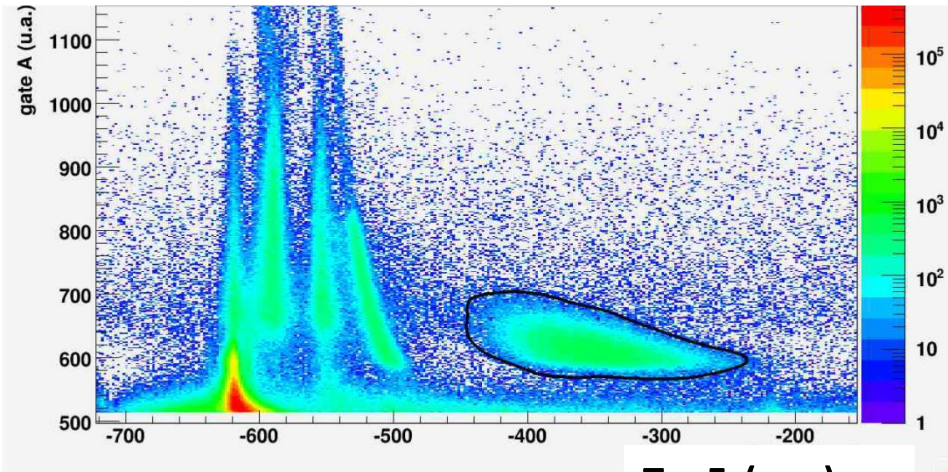
250 MeV $^{16}O + ^{116}Sn$ α-particles spectra

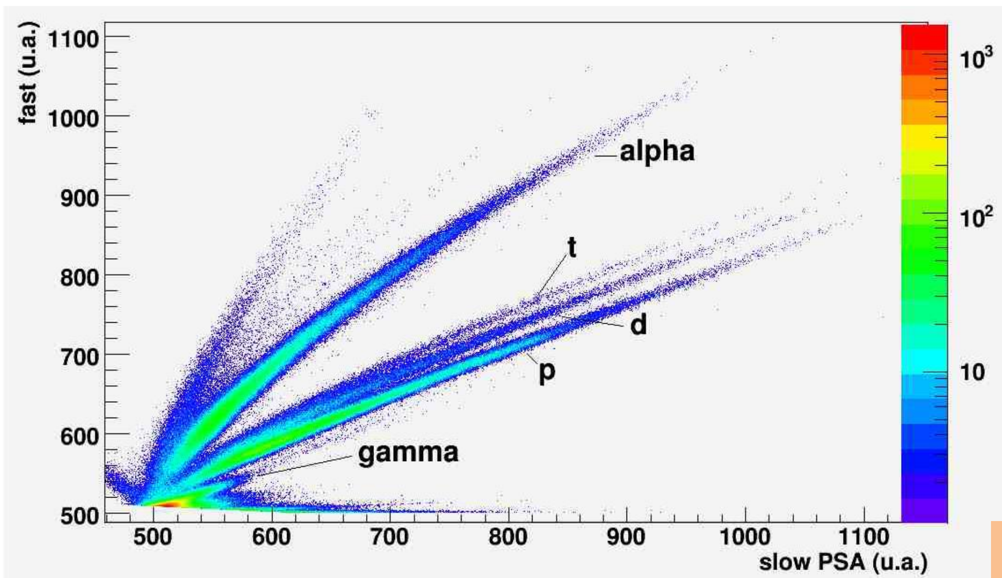
--- No α-clustering in ^{16}O
__ 10% α-clustering in ^{16}O
__ 50% α-clustering in ^{16}O
■ Exp

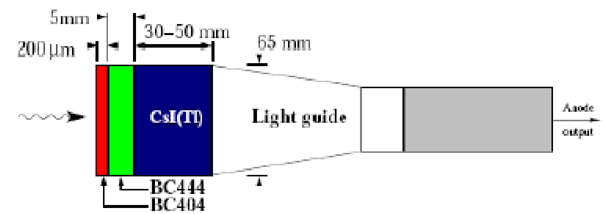


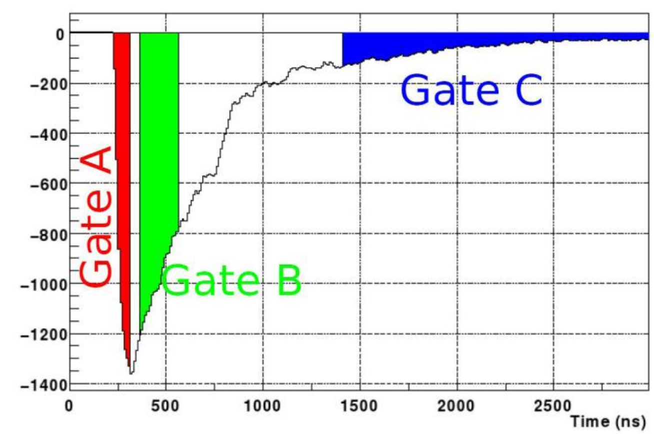
“Dynamic Dipole“: GARFIELD (digital) + Phoswich

^{16}O + ^{116}Sn E_b = 192 MeV (12 AMeV)









S. Sambi, Master Thesis, LNL and Univ. Bologna
A. Giaz et al., submitted to PRC

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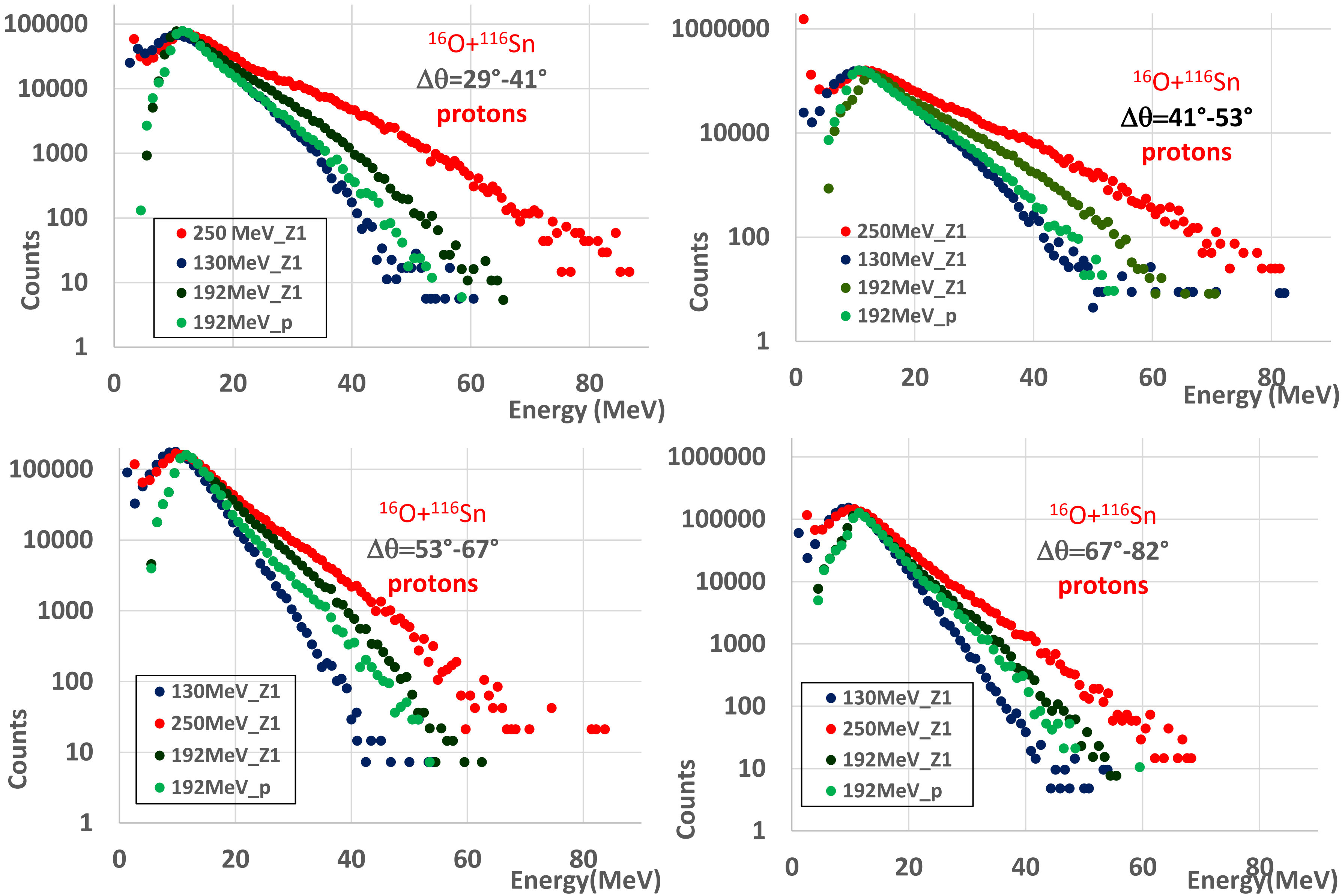
Experimental results (192 MeV):



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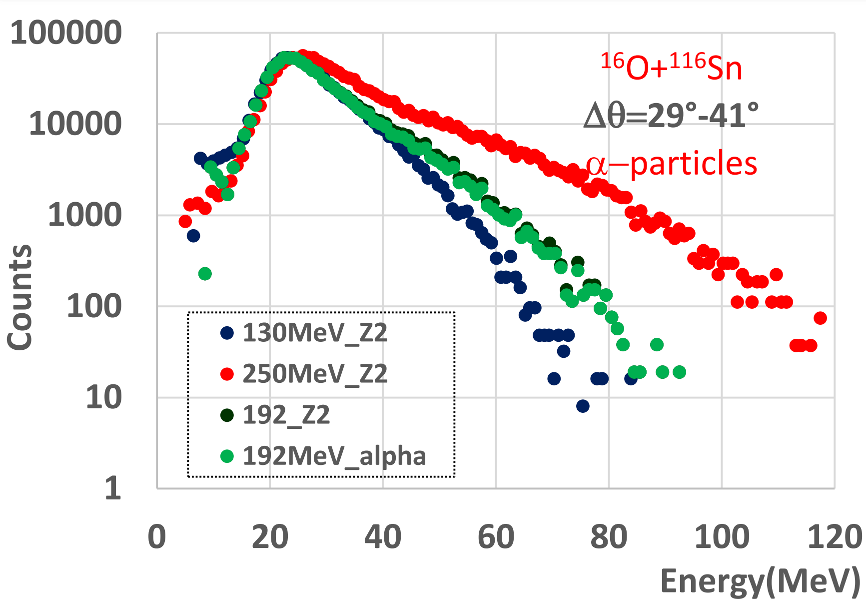

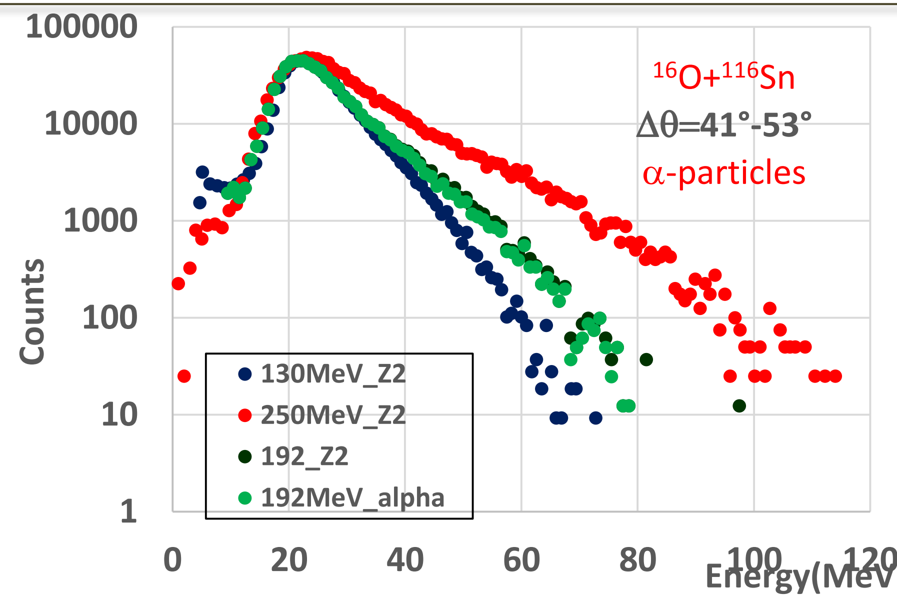

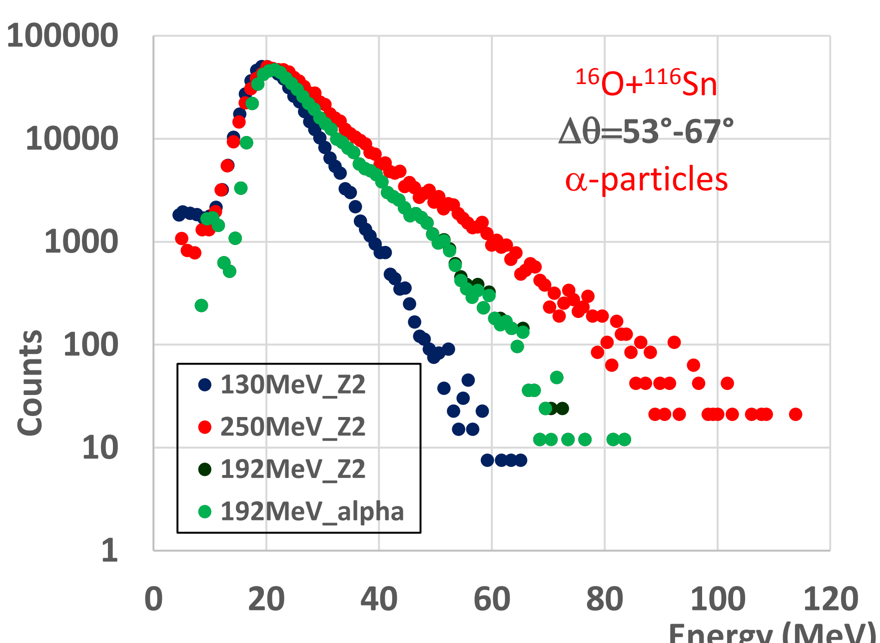

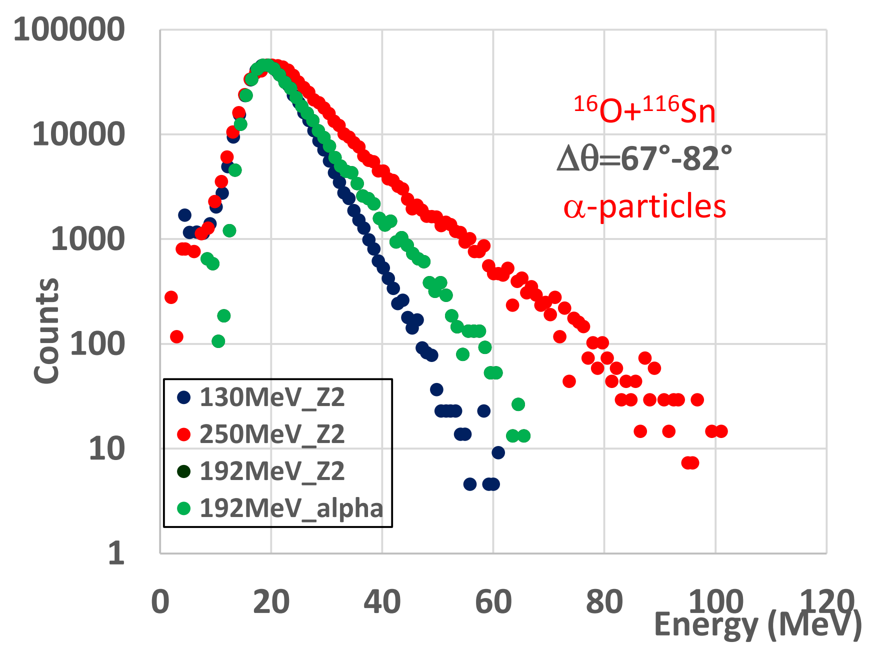

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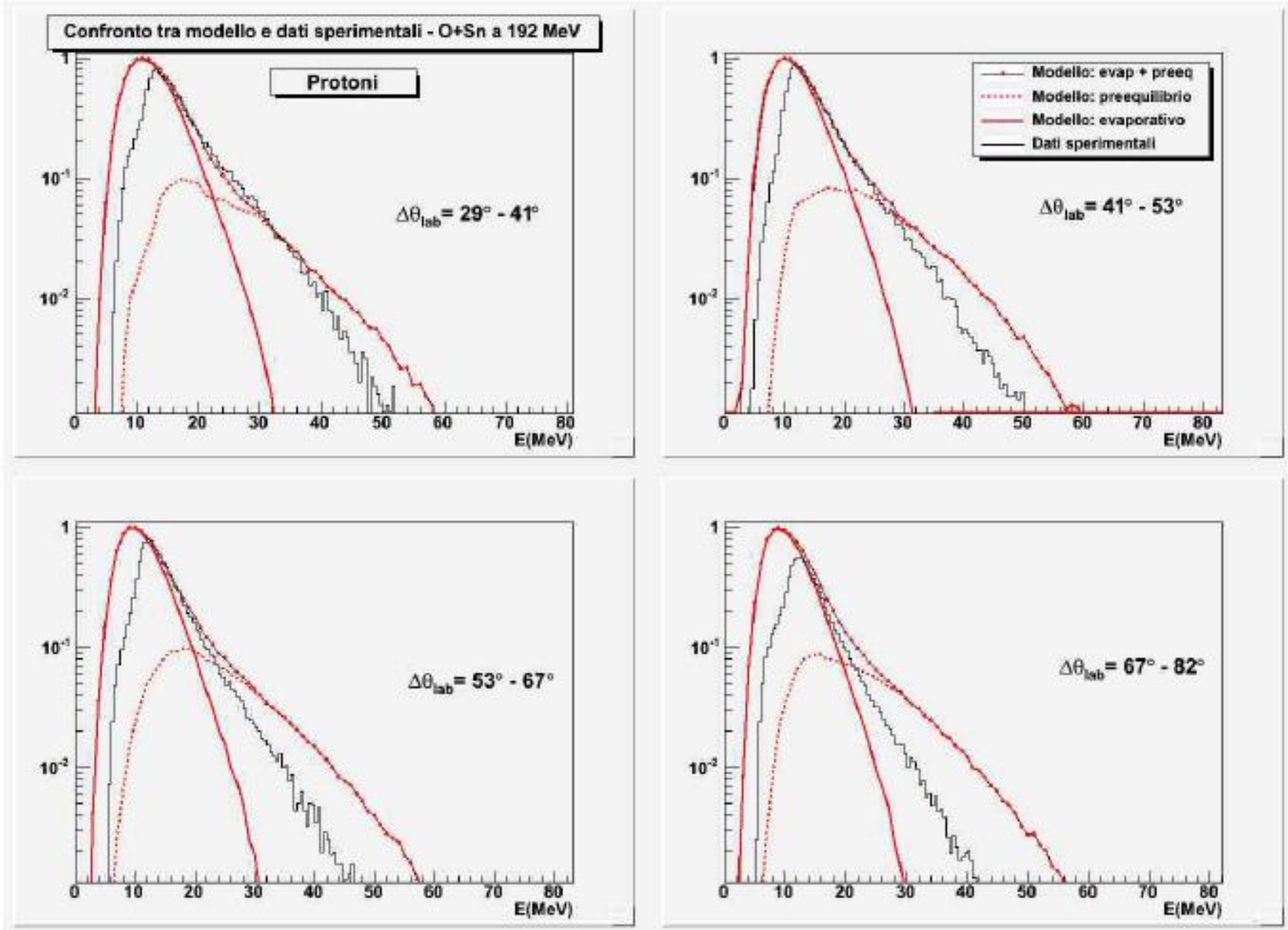
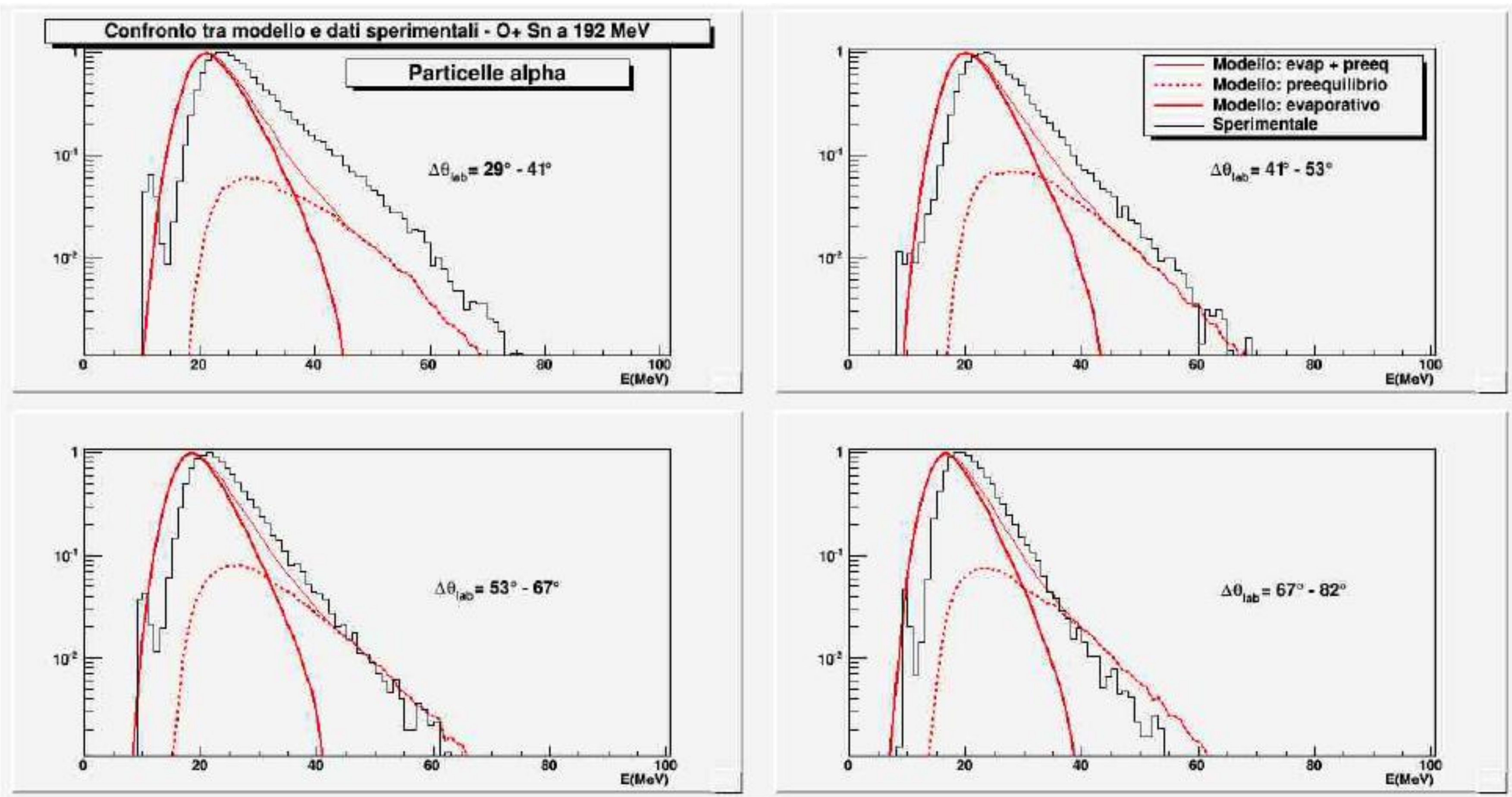
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions

Comparison with the Hybrid Exciton Model - protons (192 MeV):



S. Sambi, Master Thesis, LNL and Univ. Bologna

Comparison with the Hybrid Exciton Model – α-particles (192 MeV):



S. Sambi, Master Thesis, LNL and Univ. Bologna

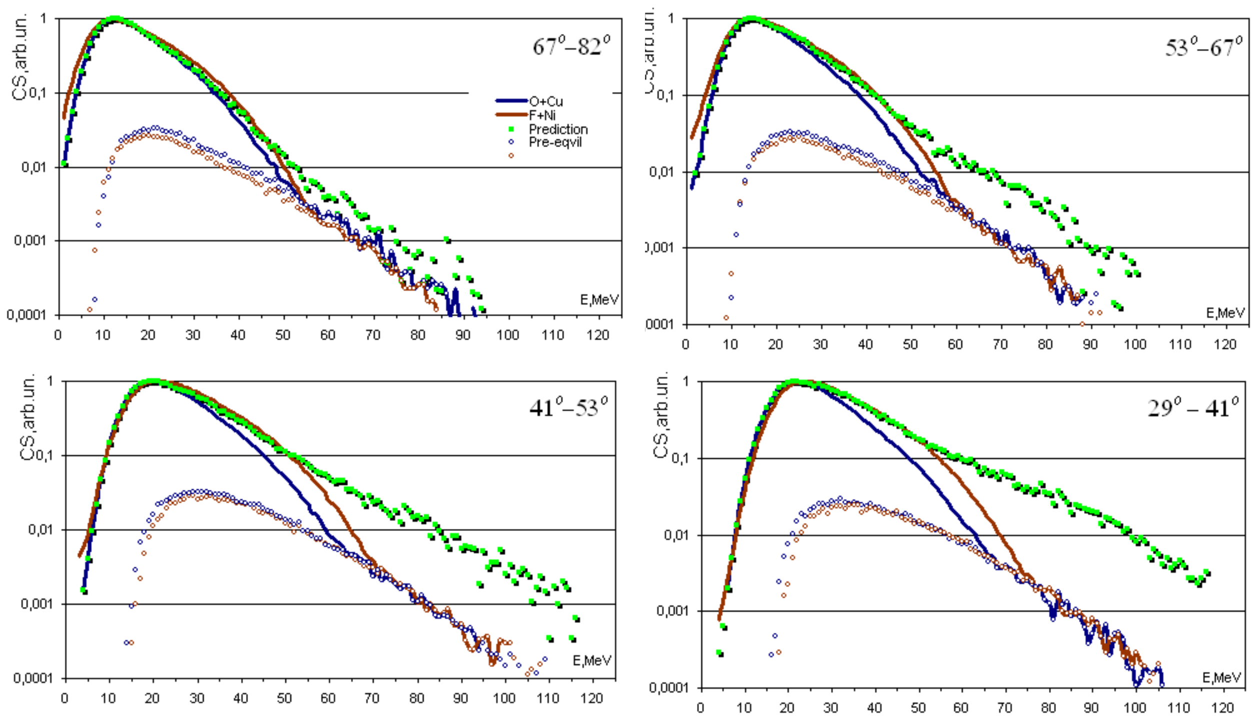
"ACLUST 2013": GARFIELD + Rco

$^{16}O + ^{65}Cu$ E_b = 256 MeV (16 MeV/u)
$^{19}F + ^{62}Ni$ E_b = 304 MeV (16 MeV/u)

CN $^{81}Rb^*$ $E^*(^{16}O)$ = 209 MeV
$E^*(^{19}F)$ = 240 MeV

Comparing the light charged particles emitted in fusion reactions where an **α–cluster projectile** (^{16}O) and **projectile without α clusterization** (^{19}F) are used.
The two systems have the **same projectile velocity.**

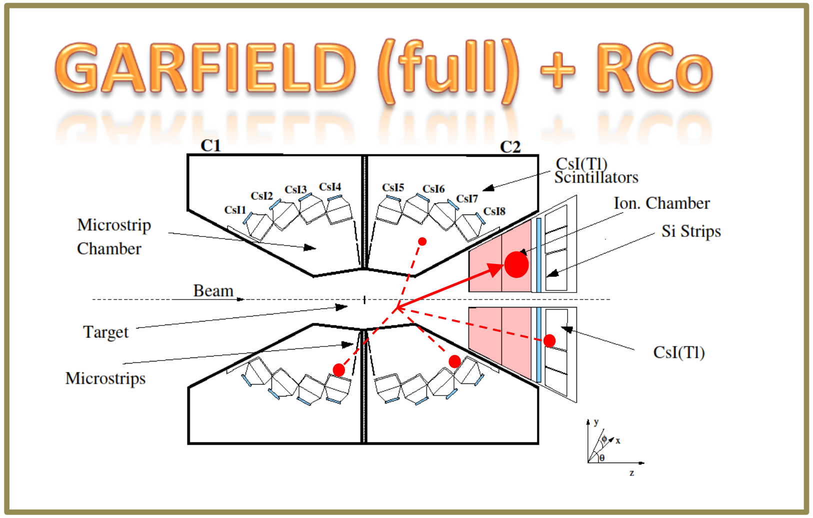
50% α-clustering in ^{16}O

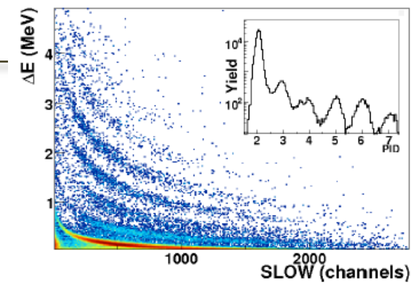


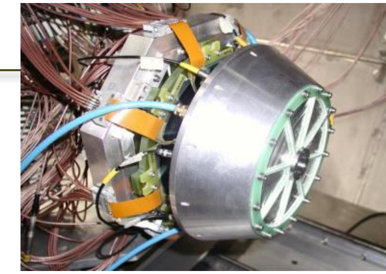
From Cabrera systematics the pre-equilibrium emission is mainly dependent on the projectile velocity
[J. Cabrera et al. Phys. Rev. C68 (2003) 034613]

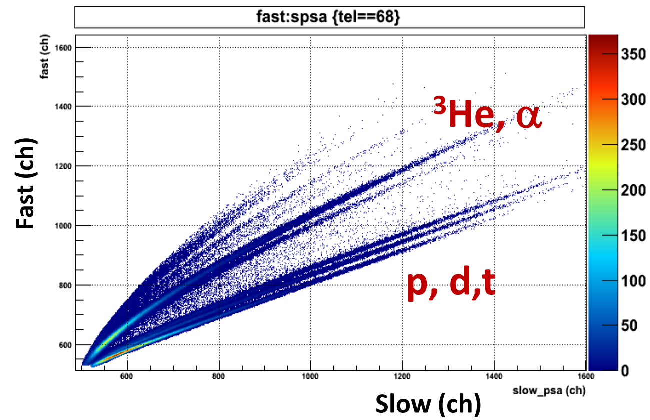
Unified Code, O.V. Fotina, Moscow State University

ACLUST experiment (2013):









Light Charged Particles **Angular distribution** an **Energy spectra** in coincidence with Evaporation Residues:

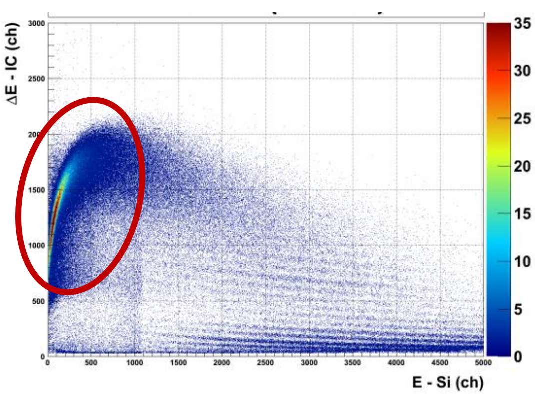
Ring Counter IC-Si $\Delta\theta = 8.6° \div 17°$ at P = 25 mbar CF_4

Ring Counter IC-Si

$\Delta\theta = 8.6° \div 17°$ at P = 25 mbar CF_4

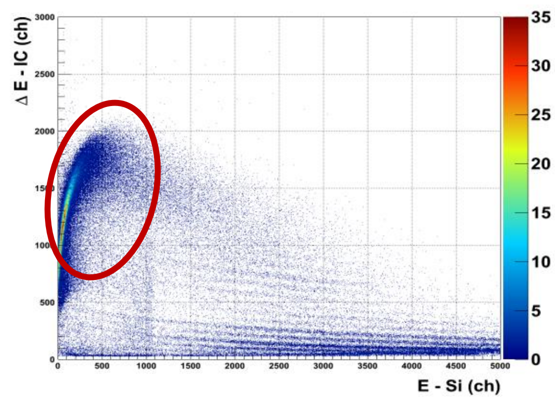
256 MeV $^{16}O + ^{65}Cu$

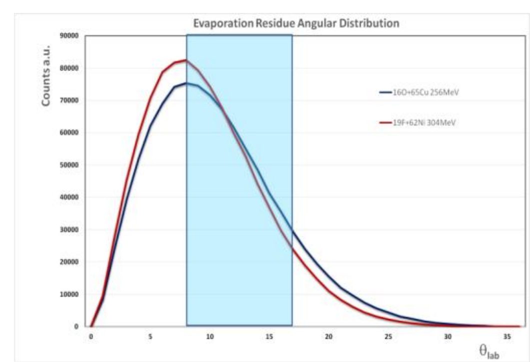
θgr =8.2°



304 MeV $^{19}F + ^{62}Ni$

θgr =7.3°





G. A.R. F.I. E. L. D.

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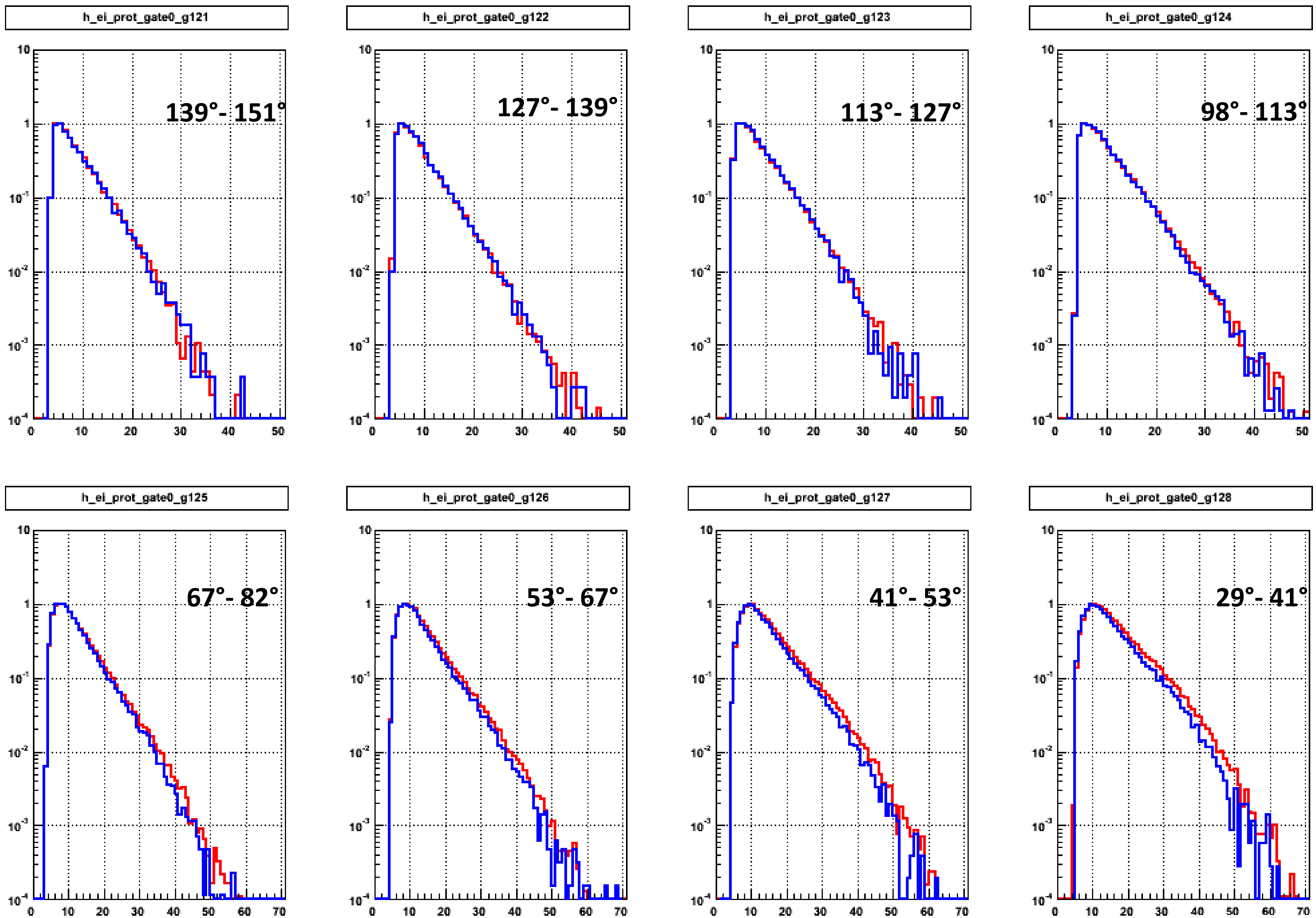
Experimental Proton spectra in Lab

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



E_{lab} (MeV)

G. AR. F. I. E. L. D.
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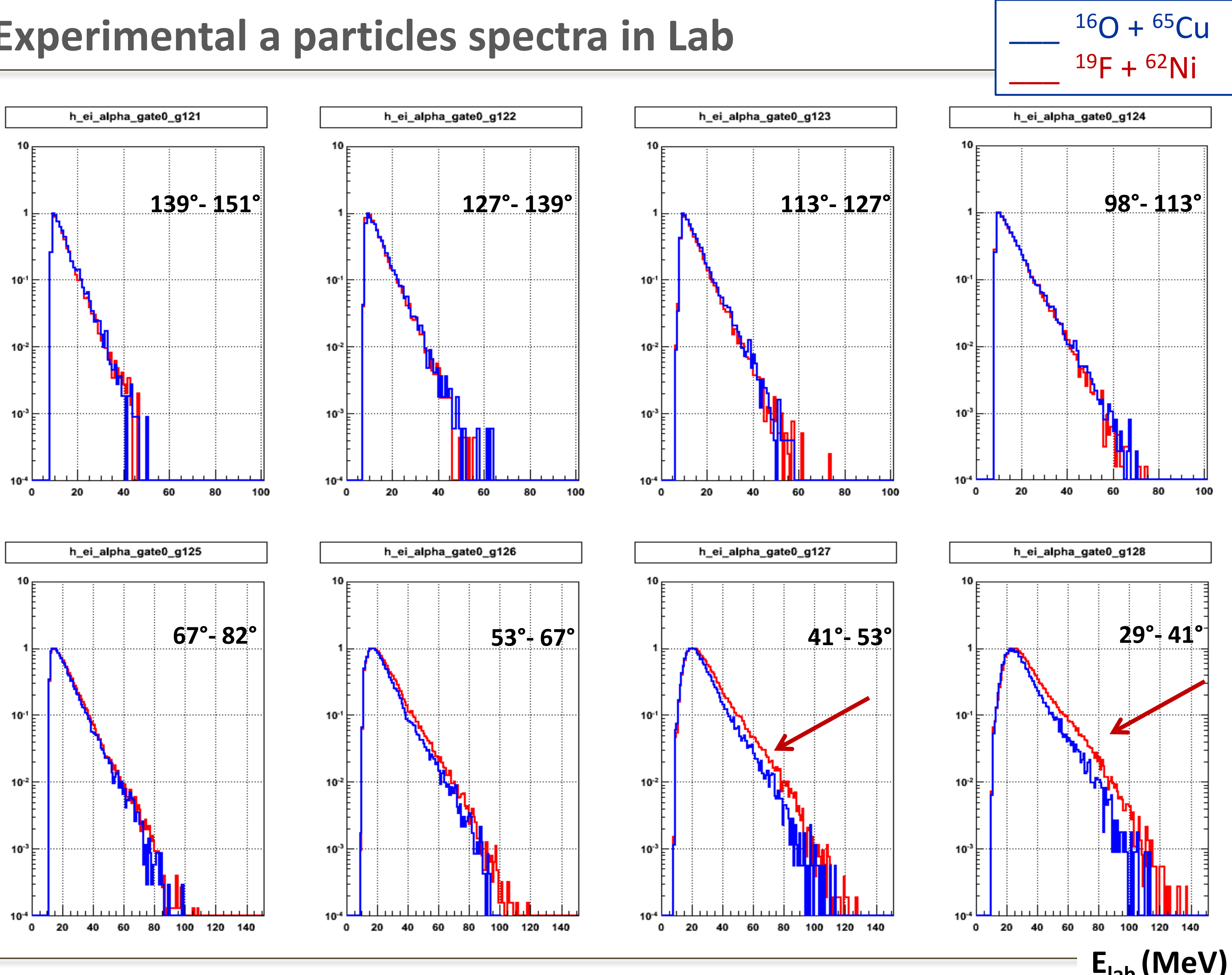
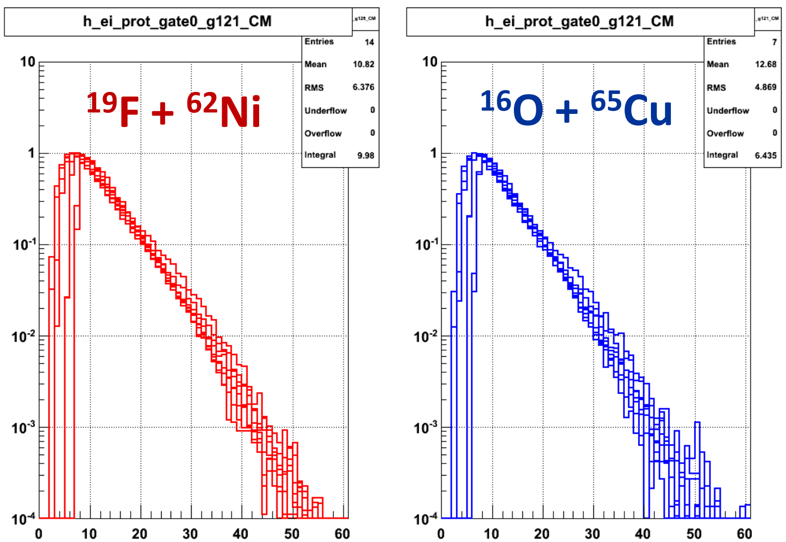
Experimental a particles spectra in Lab



CM Spectra at different angles

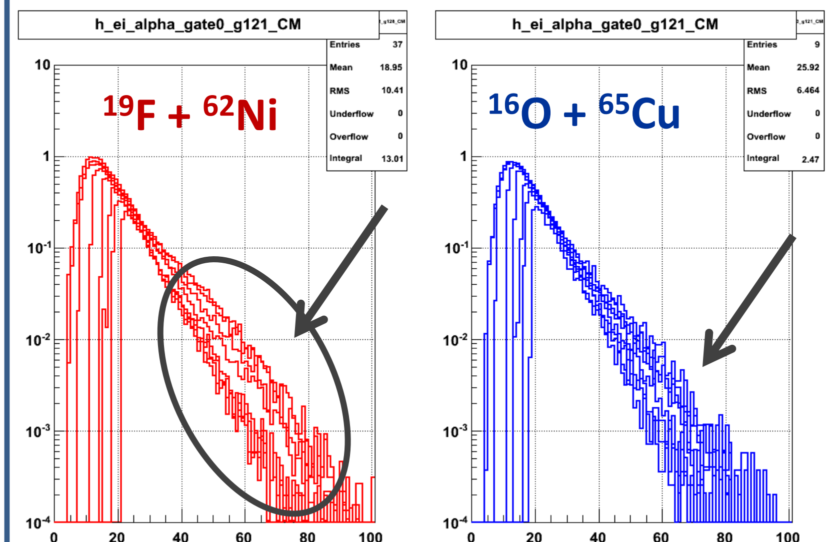
Proton in CM



E_{CM}

Very **small** pre-equilibrium contribution in proton spectra

Alpha in CM



E_{CM}

Larger pre-equilibrium contribution in **^{19}F induced reaction α-spectra** with respect to **^{16}O reaction**

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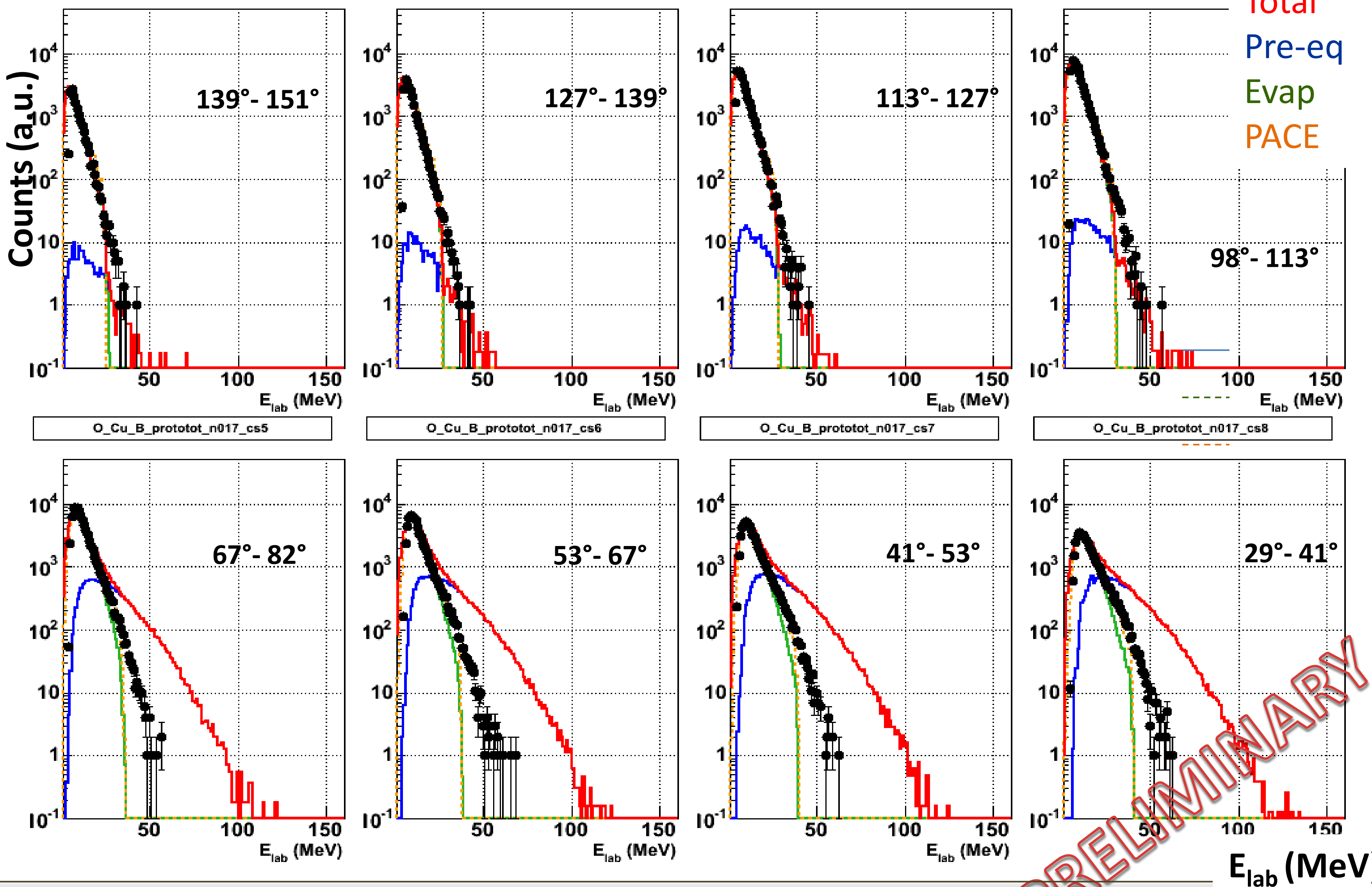
Comparison with Hybrid Exciton Model (NO clustering):

$^{16}O + ^{65}Cu$ $n_0 = 17\ 16(1)$

Protons



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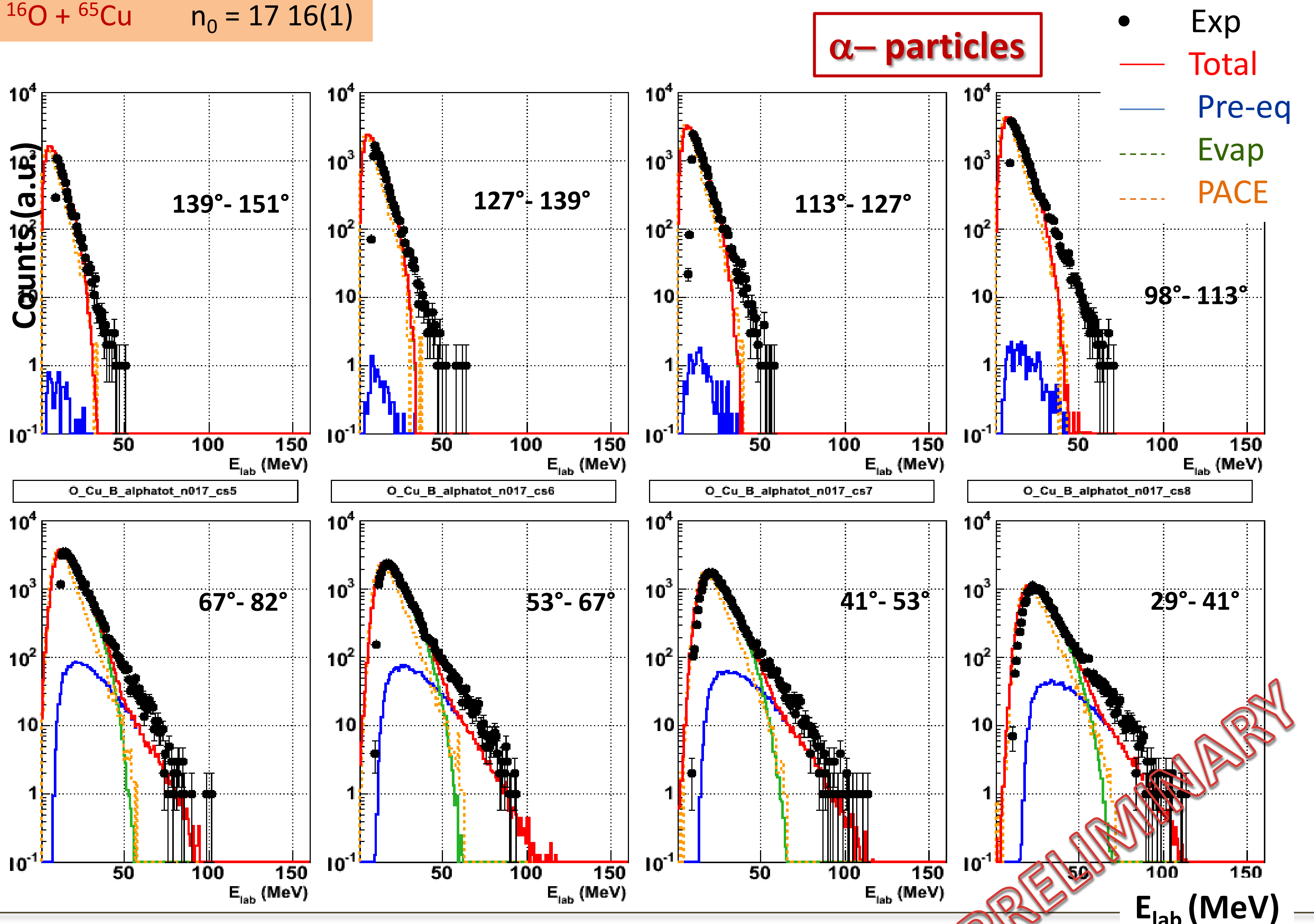
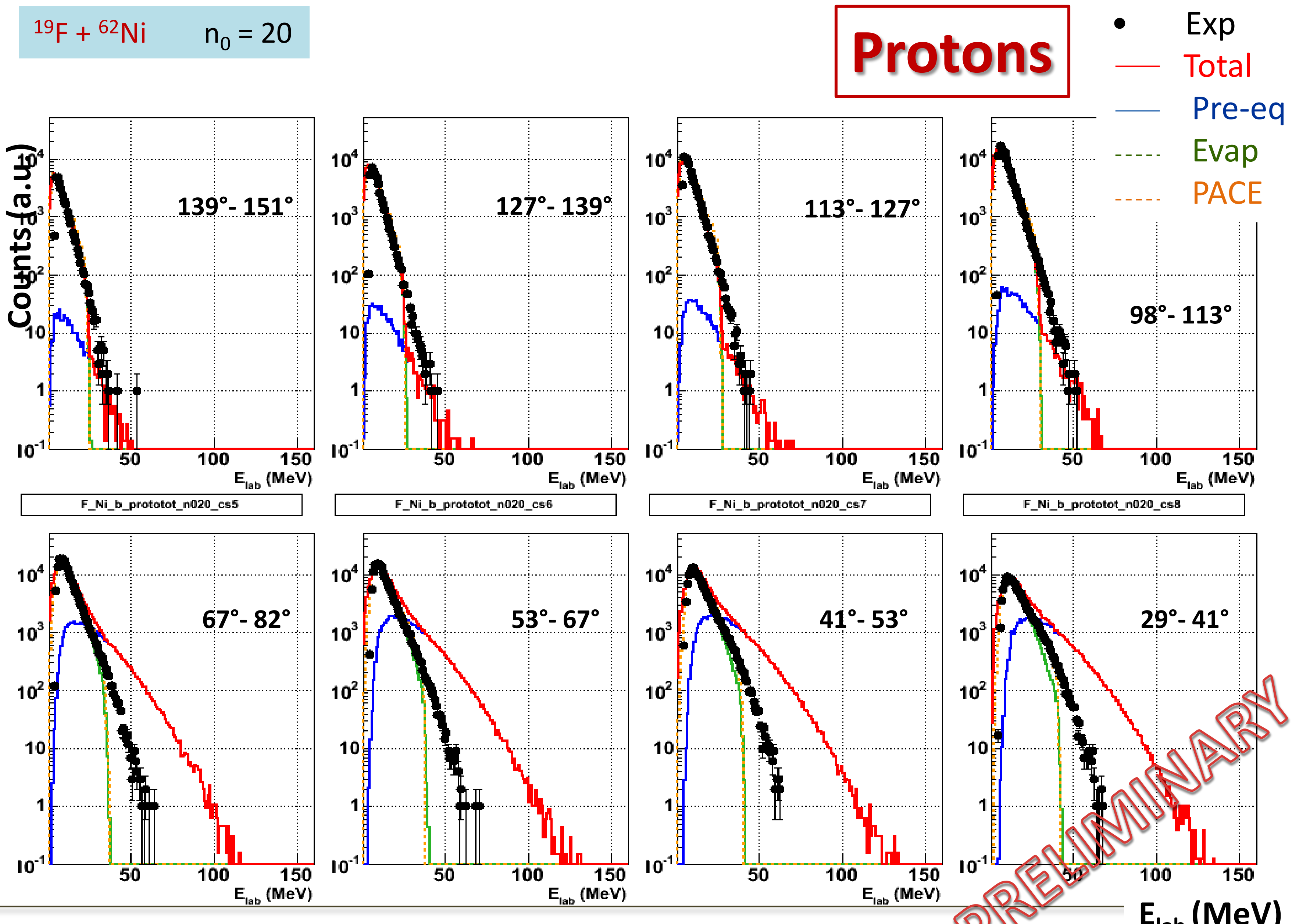


G. AR. F. I. E. L. D. General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions

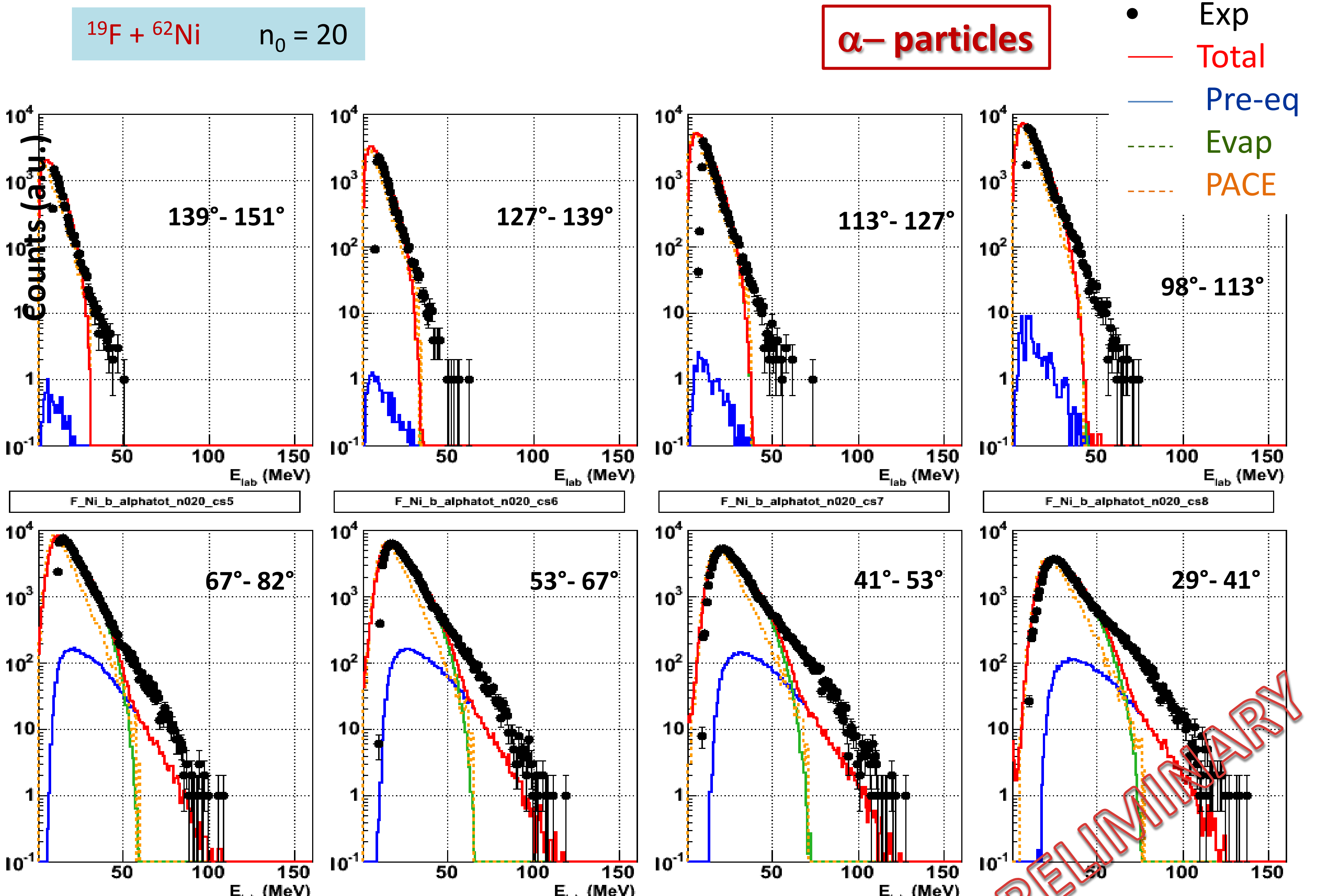
Comparison with Hybrid Exciton Model (NO clustering):

$^{19}F + ^{62}Ni$ $n_0 = 20$

Protons



Comparison with Hybrid Exciton Model (NO clustering):



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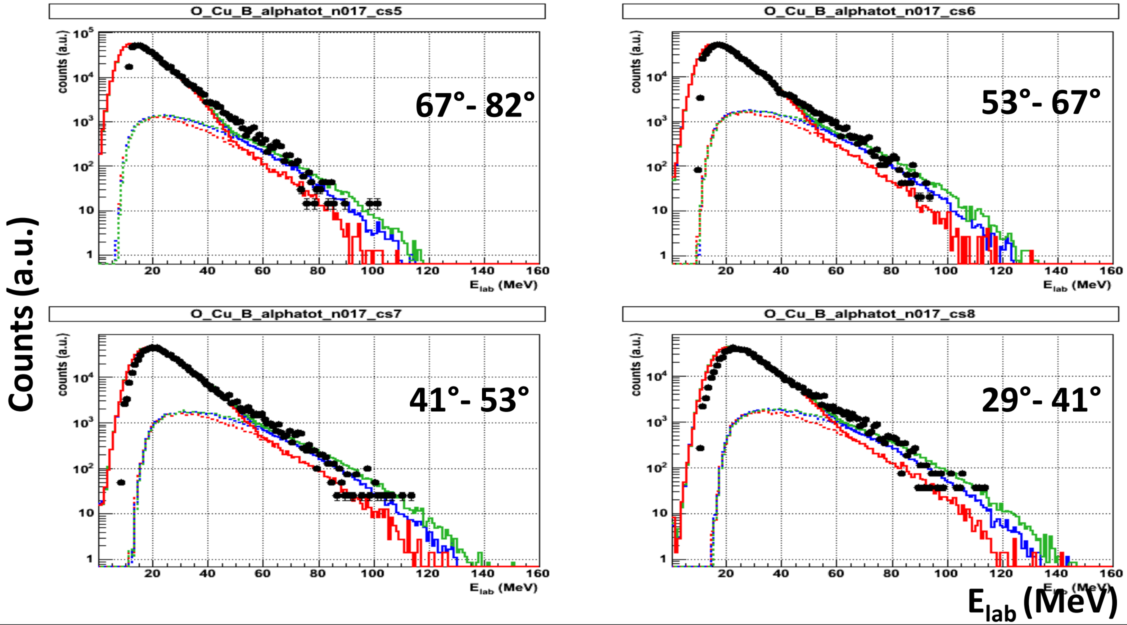
Comparison with Hybrid Exciton Model:

α– particles



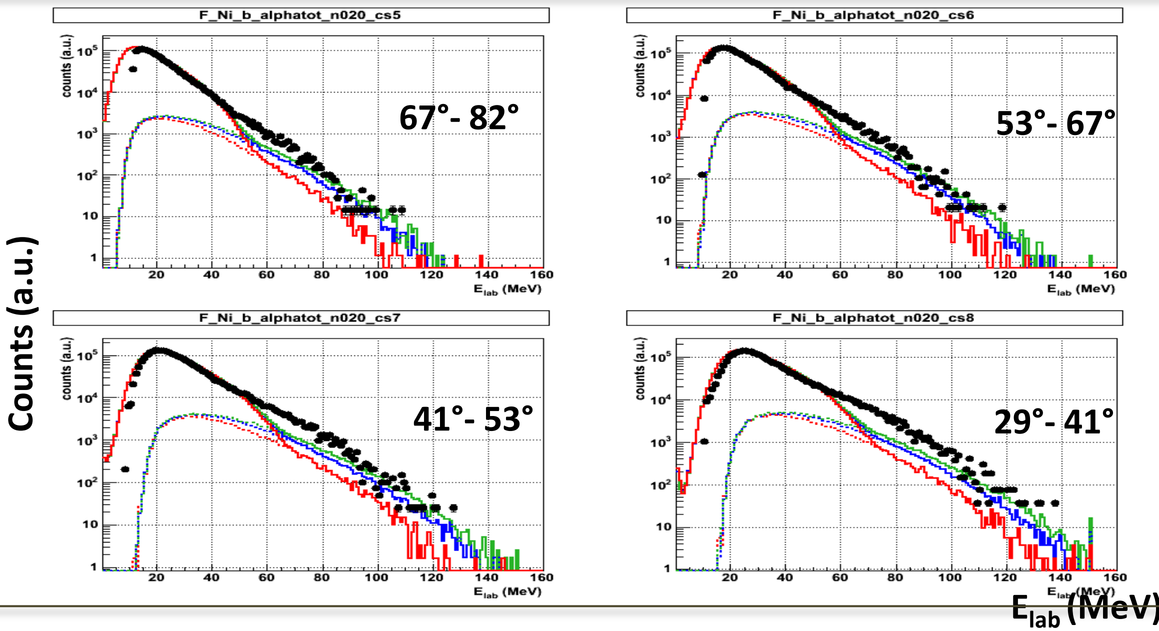
$^{16}O + ^{65}Cu$

- Exp

$n_0 = 17$ —— Total ----- Pre-eq

$n_0 = 15$ —— Total ----- Pre-eq

$n_0 = 14$ —— Total ----- Pre-eq



$^{19}F + ^{62}Ni$

- Exp

$n_0 = 20$ —— Total ----- Pre-eq

$n_0 = 18$ —— Total ----- Pre-eq

$n_0 = 17$ —— Total ----- Pre-eq

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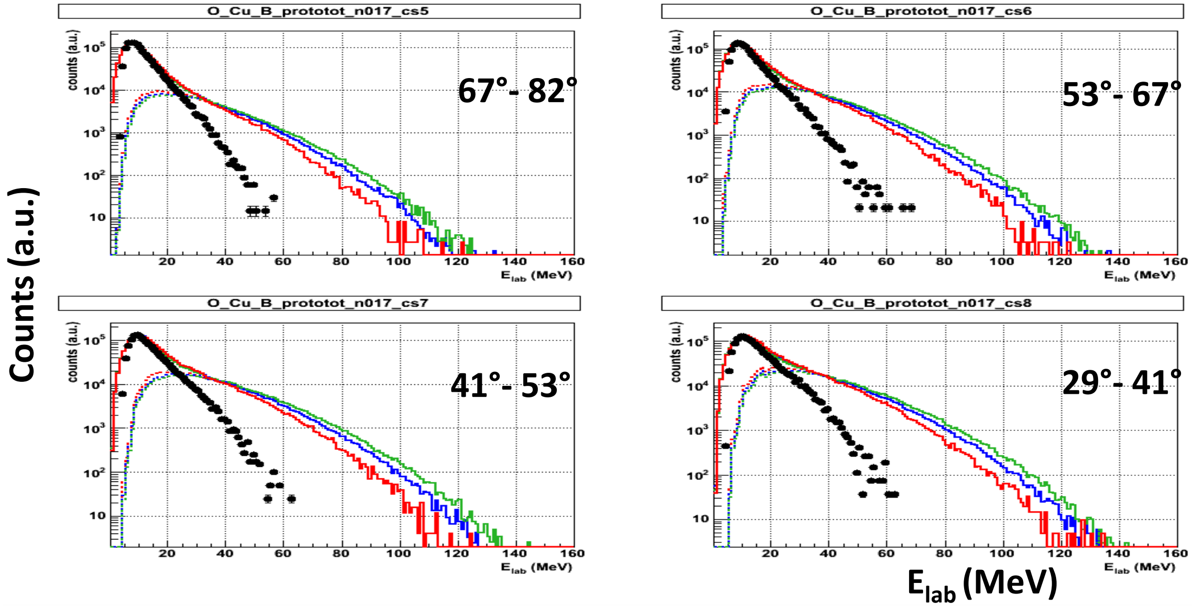
General ARray for Fragment Identification and for Emitted Light particles in Dissipative Collisions

Comparison with Hybrid Exciton Model:

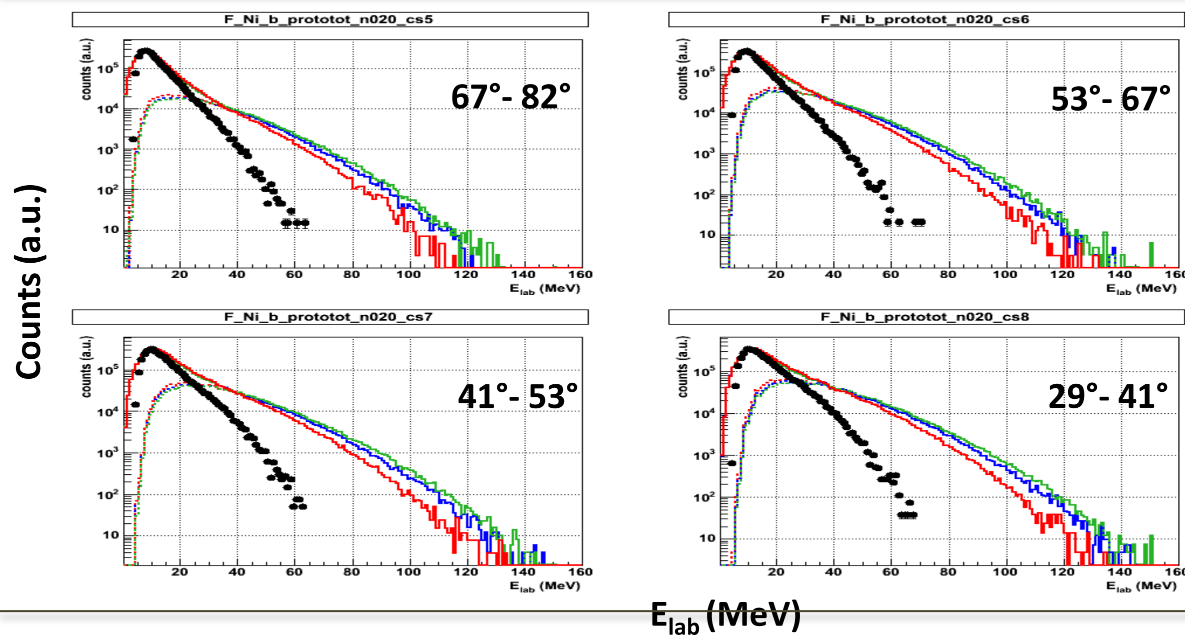
Protons



$^{16}O + ^{65}Cu$

- Exp

n_0 = 17 —— Total ----- Pre-eq
n_0 = 15 —— Total ----- Pre-eq
n_0 = 14 —— Total ----- Pre-eq



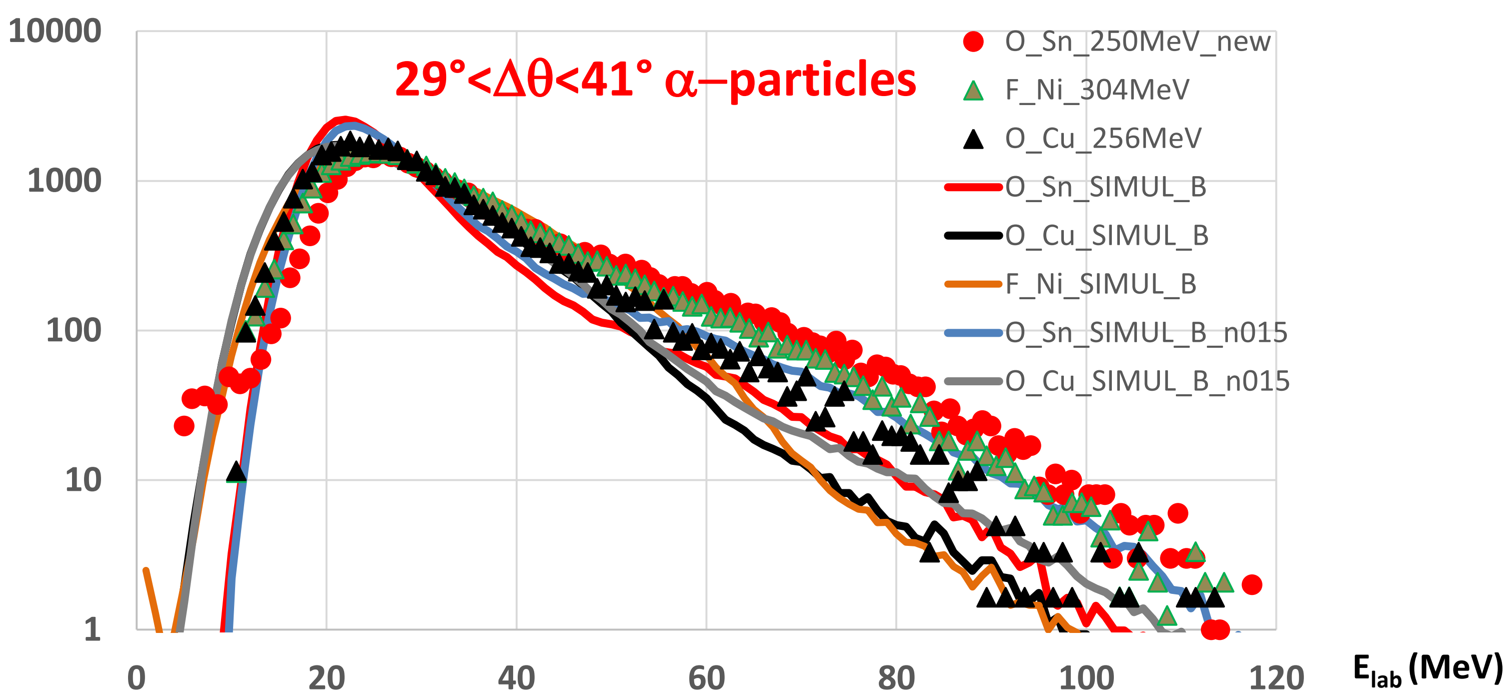
$^{19}F + ^{62}Ni$

- Exp

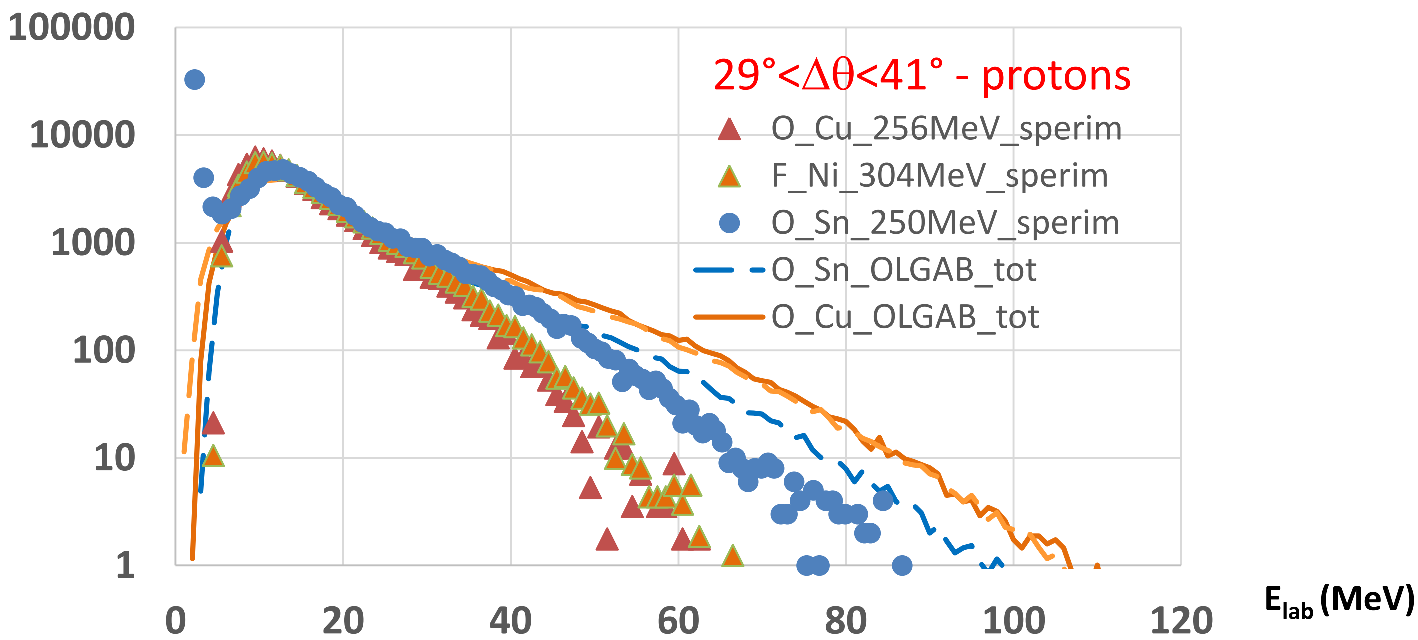
n_0 = 20 —— Total ----- Pre-eq
n_0 = 18 —— Total ----- Pre-eq
n_0 = 17 —— Total ----- Pre-eq

Summary:

- Preliminary results seem **<u>NOT</u>** <u>to confirm</u> the predicted **difference** between the two systems (16O+65Cu and 19F+62Ni) due to **α-clustering** effects in ^{16}**O** induced reactions.
- Using the same parameters the **Hybrid Exciton Model** describes resonably the <u>α-particles</u> but strongly overestimates the <u>protons.</u> **Cluster preformation** has to be considered to take into account the alpha – protons emission competition.



Summary:



Analysis is in progress….

- To extract energy spectra for all particles **p**, **d**, **t**, **^{3}He**, **α** also for the most forward angles of the Rco where the pre-equilibrium emission and any possible difference are maximized.
- To study **angular** and **energy correlations** of the emitted particles event-by-event.
- To perform more **selective coincidences** with **evaporation residues**, as a function of their energies and of the detected angles.
- To **complete** the Hybrid Exciton Model **calculations** for all particles and for all the measured angles.

Outlook: SPES

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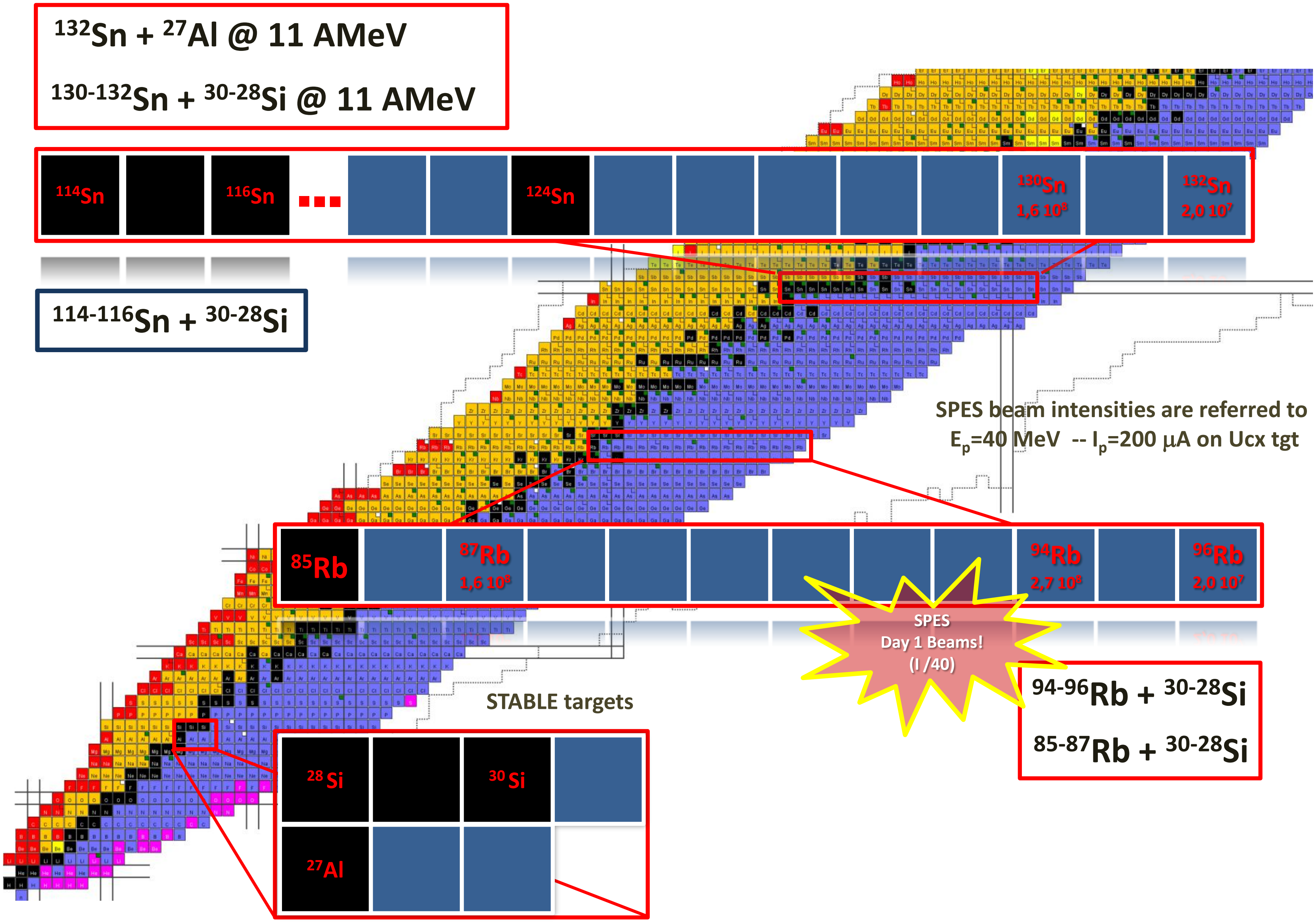

Collaboration

F. Gramegna[1], D. Fabris[2], T. Marchi[1], M. Degerlier[3], V.L. Kravchuk[4], M. Cinausero[1], S. Appannababu[1], M. Bruno[5], M. D'Agostino[5], L. Morelli[5], G. Casini[6], S. Barlini[6], M. Bini[6], A. Olmi[6], G. Pasquali[6], S. Piantelli[6], G. Poggi[6], S. Valdrè[6], O.V. Fotina[7], S.A. Goncharov[7], D.O. Eremenko[7], O.A. Yuminov[7], Yu.L. Parfenova[7], S.Yu. Platonov[7], V.A. Drozdov[7], E. Vardaci[8]

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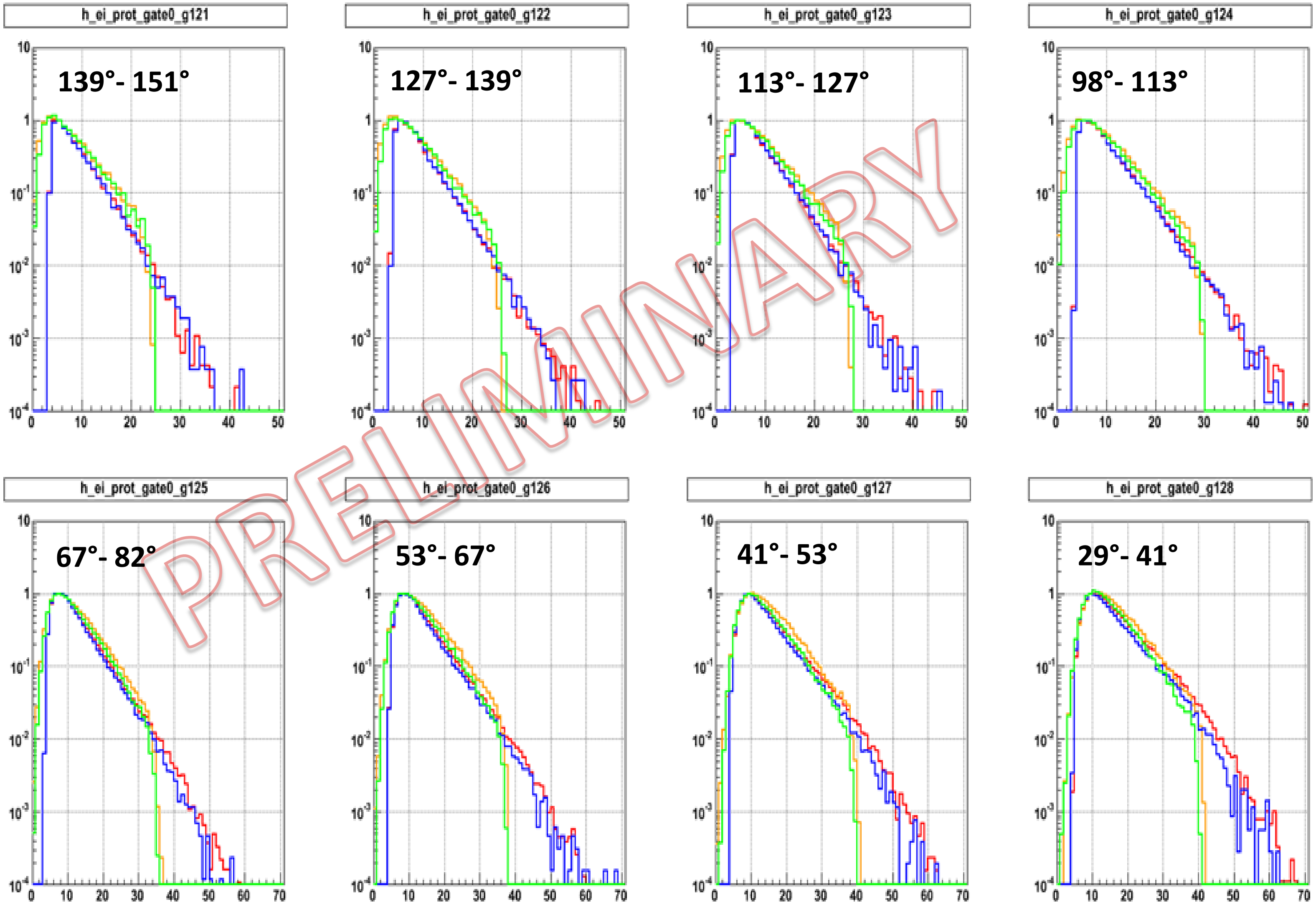
[4]*National Research Center "Kurchatov Institute", Moscow, Russia*
[5]*Dipartimento di Fisica, Università di Bologna and INFN sezione di Bologna, Bologna, Italy*
[6]*Dipartimento di Fisica, Università di Firenze and INFN sezione di Firenze, Firenze, Italy*
[7]*Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*
[8] *Dipartimento di Scienze Fisiche, Università di Napoli "Federico II", Napoli, Italy*

ACLUST experiment (2013):

$^{16}O + ^{65}Cu$ (blue)
$^{19}F + ^{62}Ni$ (red)
$^{16}O + ^{65}Cu$ PACE (green)
$^{19}F + ^{62}Ni$ PACE (orange)



E_{lab} (MeV)

Proton spectra in Lab

[D. Fabris, IWNDT 2013, Texas A&M University, College Station, Texas]

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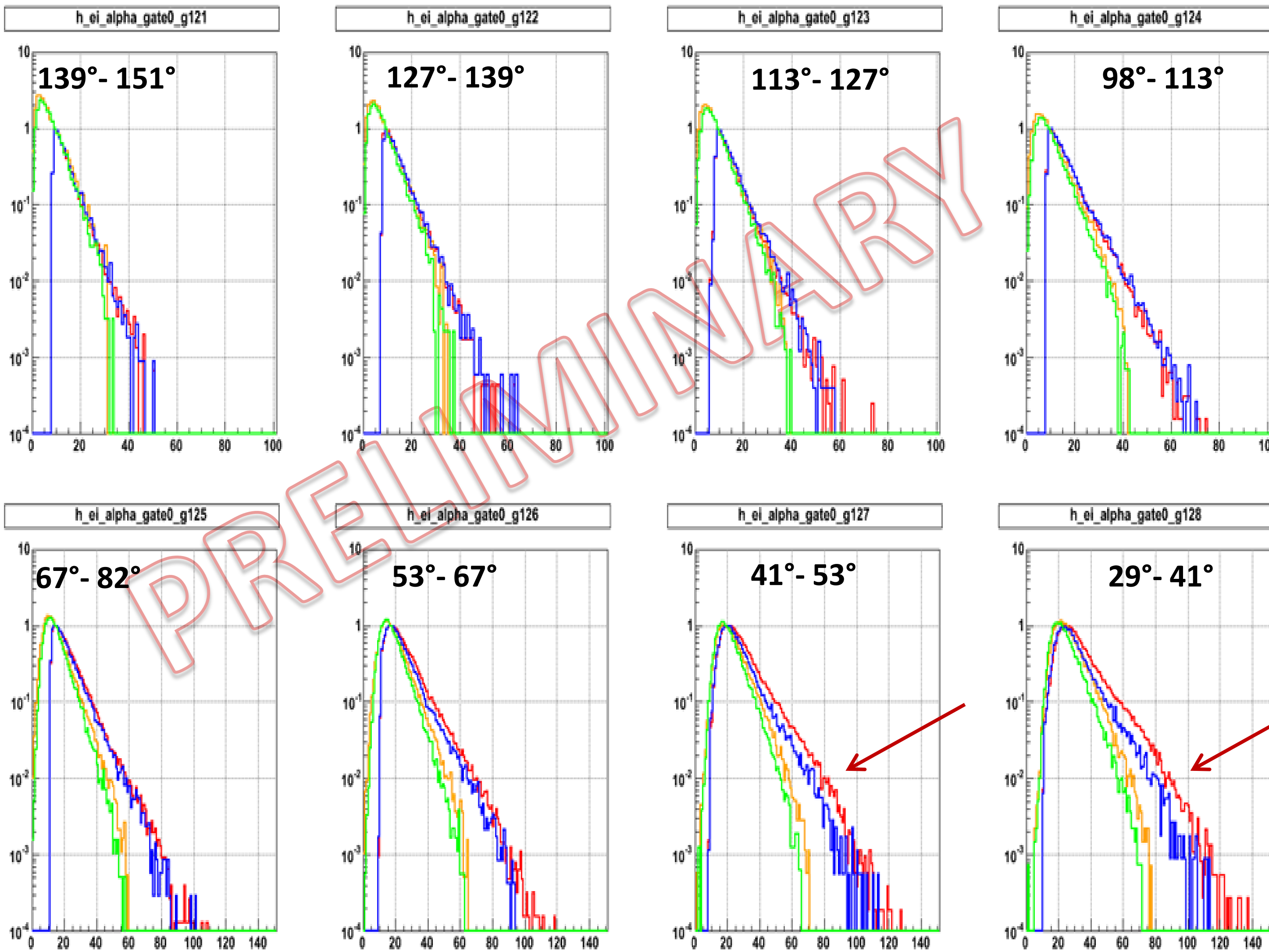
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions

ACLUST experiment (2013):

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



E_{lab} (MeV)

Alpha spectra in Lab

[D. Fabris, IWNDT 2013, Texas A&M University, College Station, Texas]

G. AR. F. I. E. L. D.
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions

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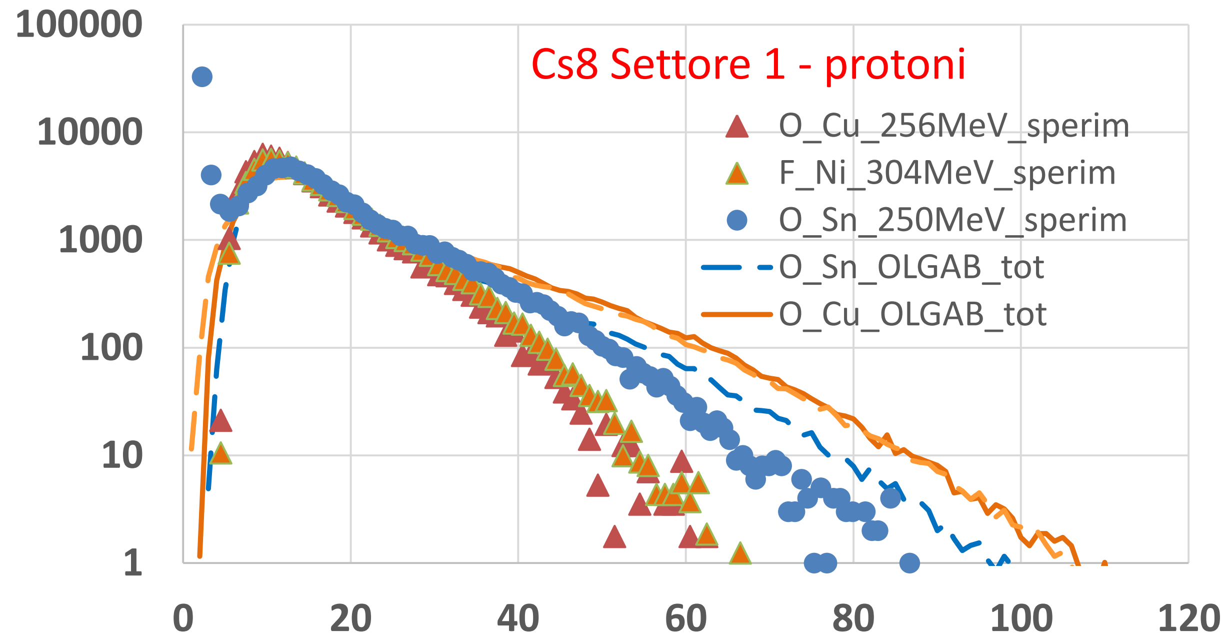
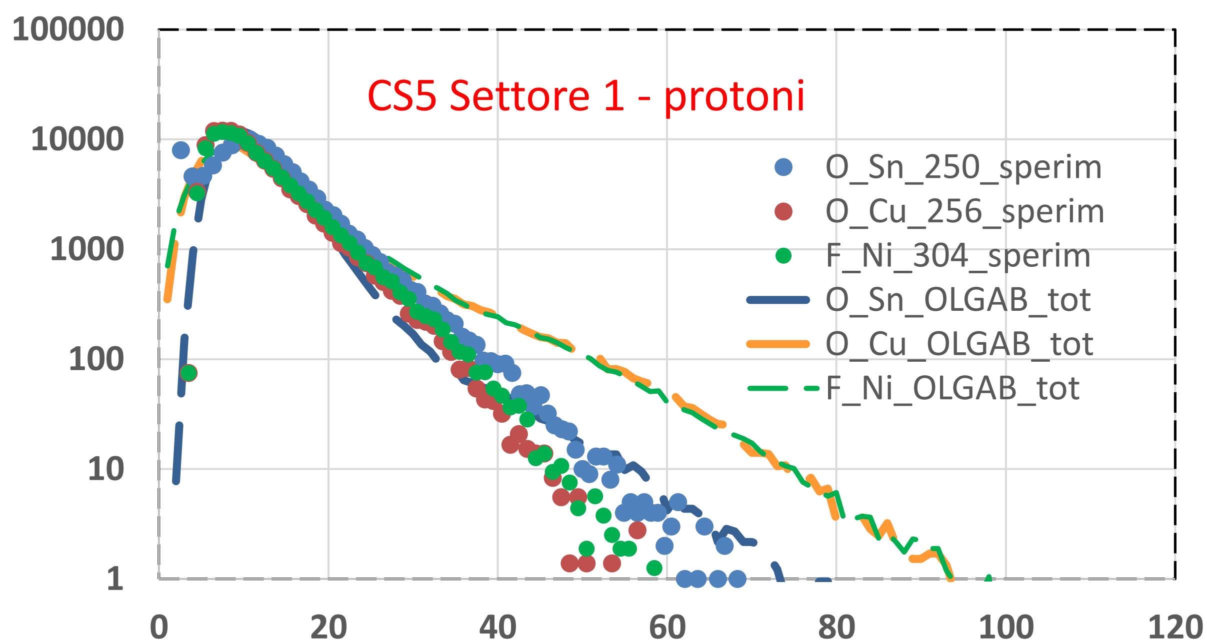
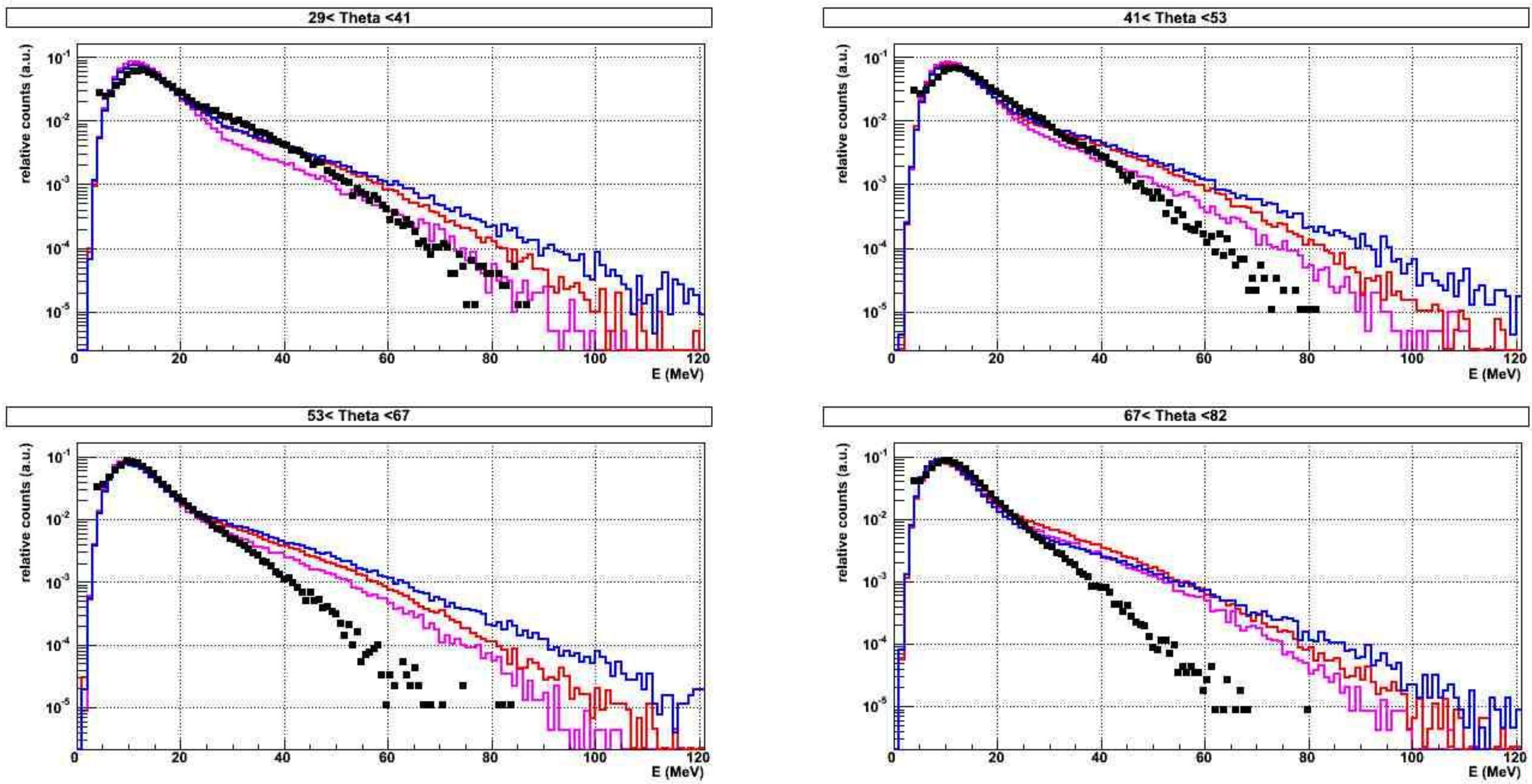
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions





Experimental results (2002-2003) – with clustering:

250 MeV ^{16}O + ^{116}Sn **proton** spectra



Light particle emission mechanisms

Moving source analysis

1) Evaporative (statistical equilibrium) contribution

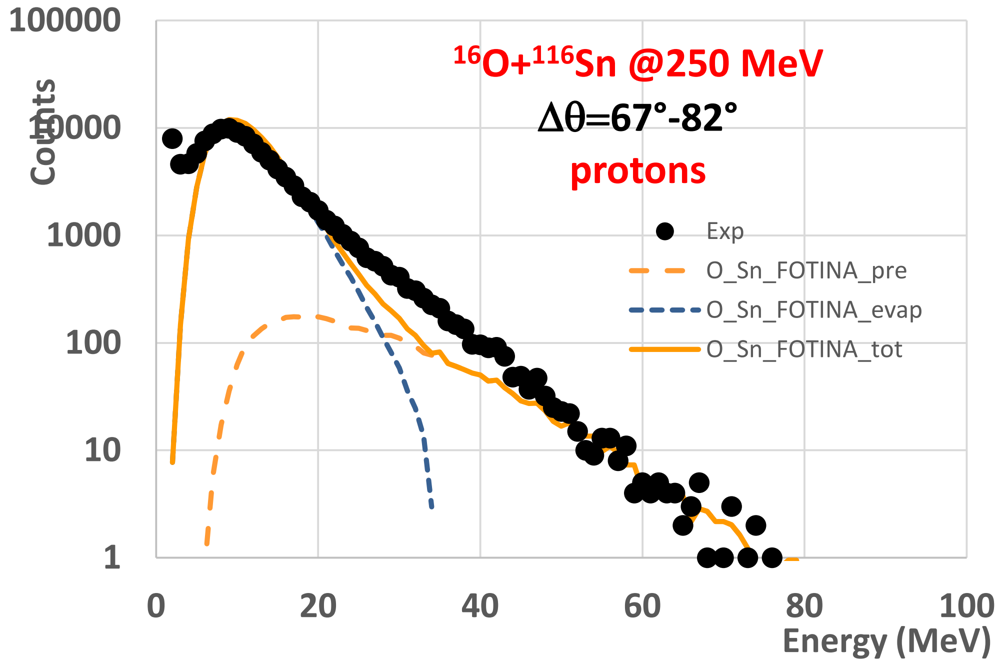
$$\frac{d^2 N_2}{d\Omega dE} = \frac{N_2}{4\pi T_2^2}(E - V_{c2}) e^{\frac{-(E-V_{c2})}{T_2}} (1 + \alpha_2 P_2(\cos\vartheta))$$

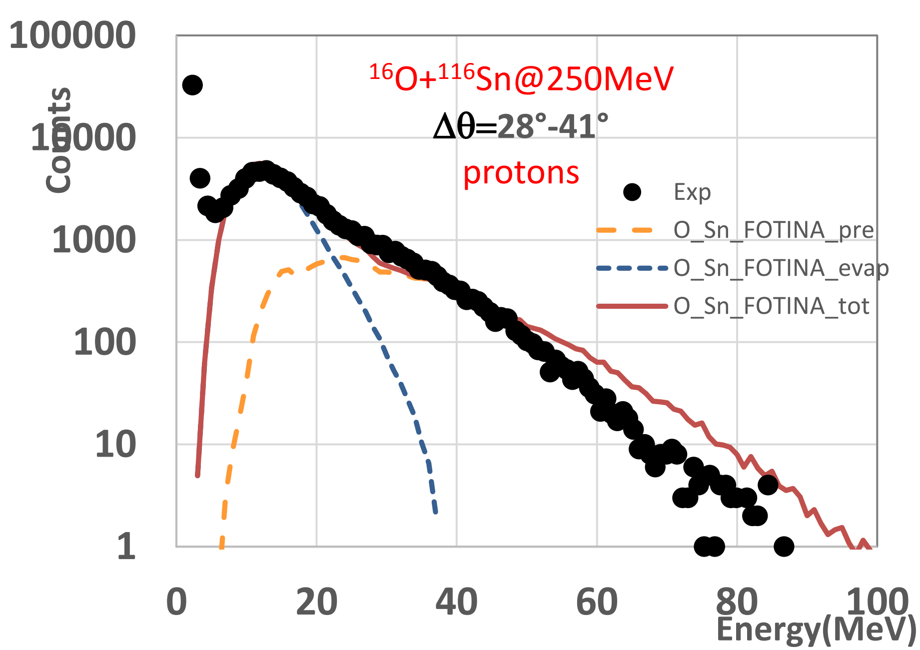
N_2, T_2, V_{c2} – yield, temperature, Coulomb energy parameter for the evaporative particles

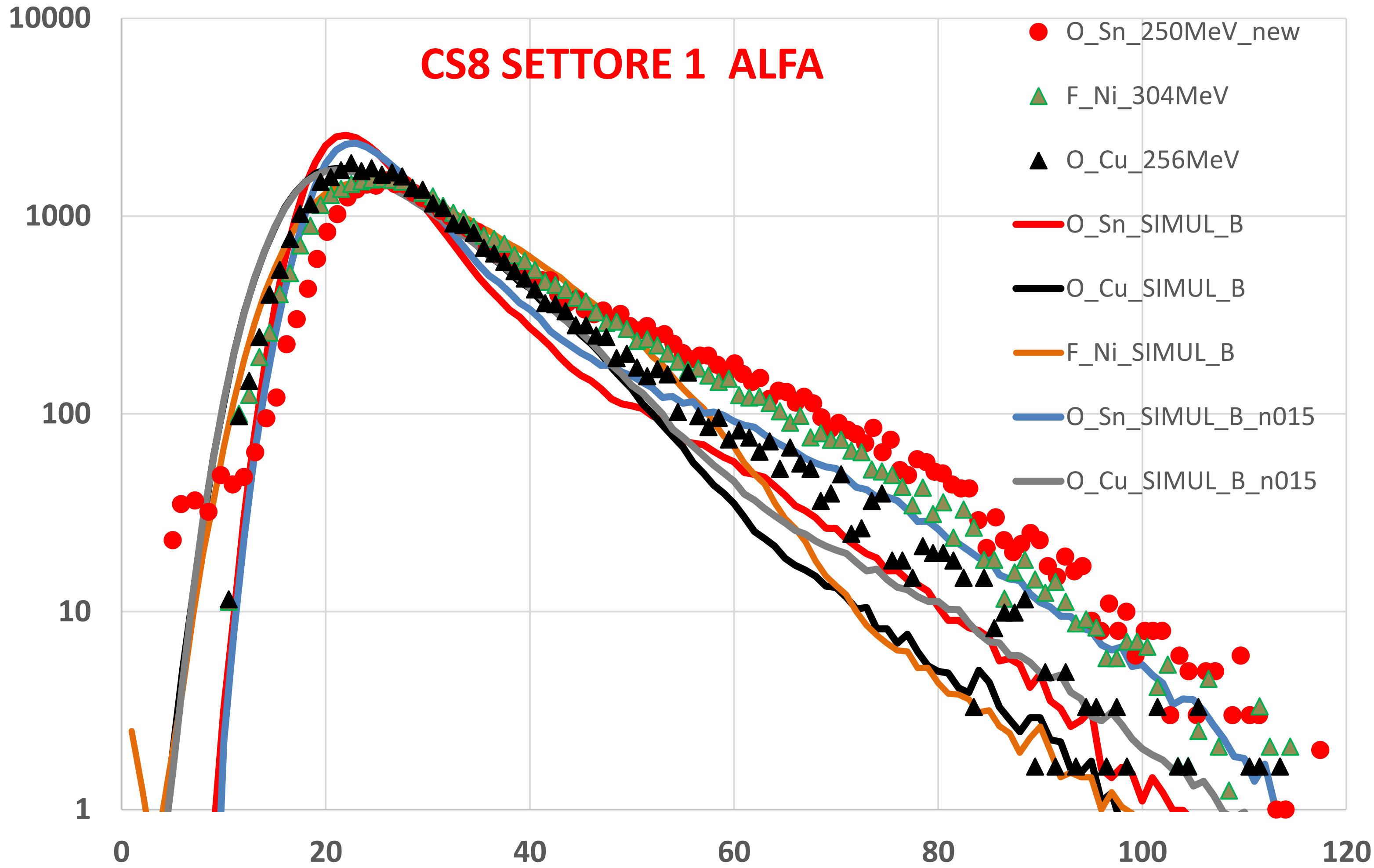
2) Pre-equilibrium contribution

$$\frac{d^2 N_1}{d\Omega dE} = \frac{N_1}{2(\pi T_1)^{3/2}} \sqrt{(E - V_{c1})} e^{\frac{-(E-V_{c1})}{T_1}}$$

N_1, T_1, V_{c1} – yield, temperature, Coulomb energy parameter for the preequilibrium particles


100000
10000
1000
100
10
1
Counts
16O+116Sn @250 MeV
Δθ=67°-82°
protons
Exp
O_Sn_FOTINA_pre
O_Sn_FOTINA_evap
O_Sn_FOTINA_tot
0
20
40
60
80
100
Energy (MeV)


100000
10000
1000
100
10
1
Counts
16O+116Sn@250MeV
Δθ=28°-41°
protons
Exp
O_Sn_FOTINA_pre
O_Sn_FOTINA_evap
O_Sn_FOTINA_tot
0
20
40
60
80
100
Energy(MeV)



CS8 SETTORE 1 ALFA
10000
1000
100
10
1
0
20
40
60
80
100
120
O_Sn_250MeV_new
F_Ni_304MeV
O_Cu_256MeV
O_Sn_SIMUL_B
O_Cu_SIMUL_B
F_Ni_SIMUL_B
O_Sn_SIMUL_B_n015
O_Cu_SIMUL_B_n015