Light Particle Emission Mechanisms and Alpha Clustering in Nuclei

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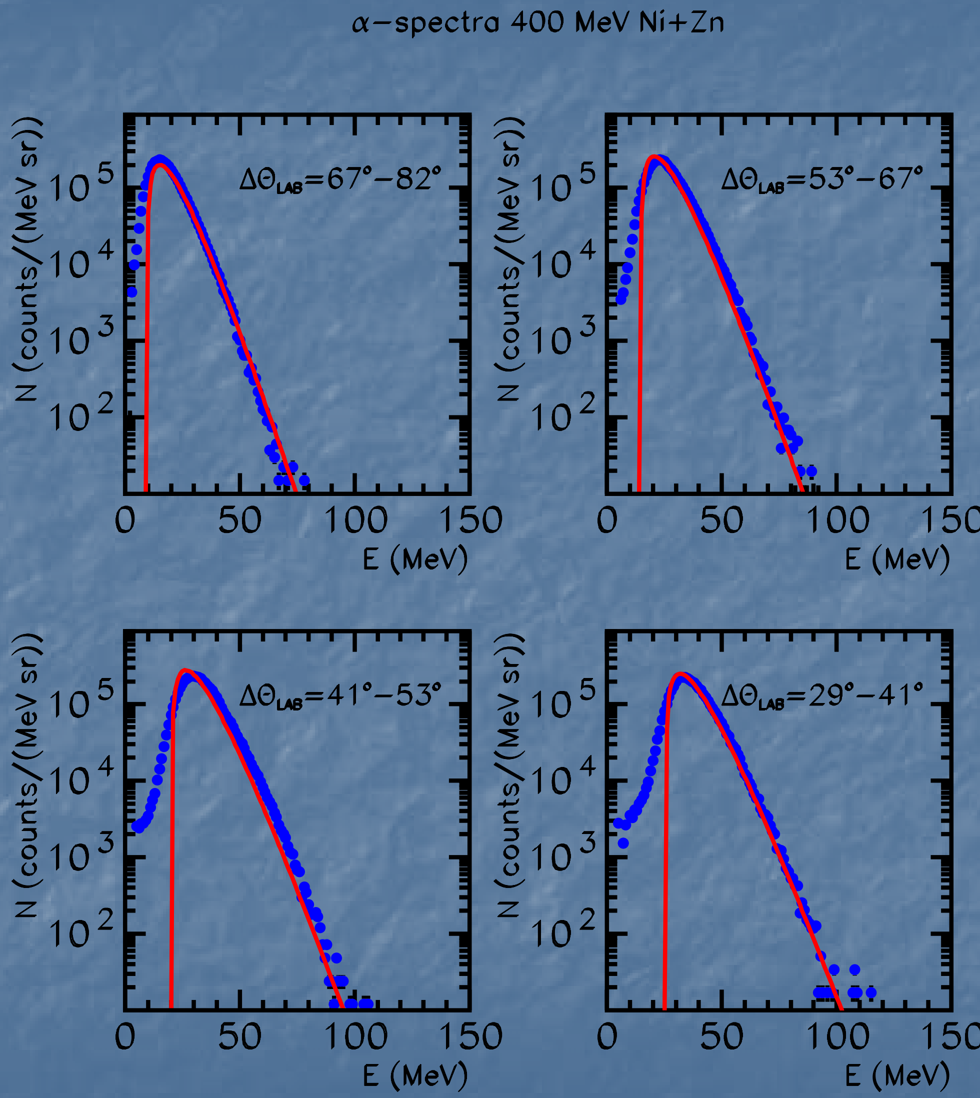
Roma 29.04.2010

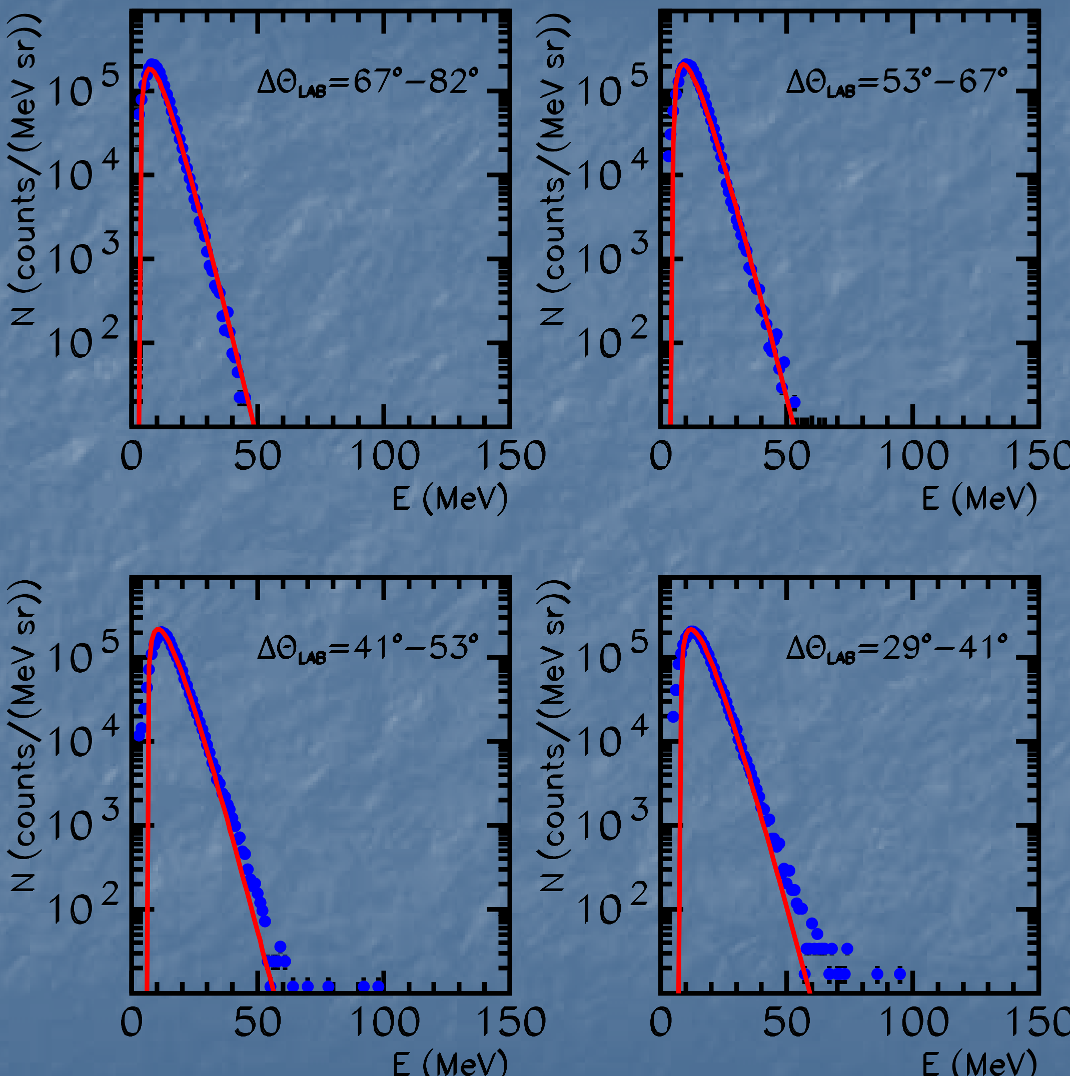
Systems studied

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
$^{16}O+^{116}Sn$	*8.1*	114	100	3.96	0.48
$^{16}O+^{116}Sn$	12.0	169	155	4.82	0.58
$^{16}O+^{116}Sn$	15.6	220	206	5.49	0.67

Part 1. Evaporative emission (Past)



p–spectra 400 MeV Ni+Zn



Results

Reaction	LCP	M (EXP)	M (PACE4) (PACE2 – OF)
8.1 MeV/u $^{16}O+^{116}Sn$	p	0.98 ± 0.09	1.43 1.28
8.1 MeV/u $^{16}O+^{116}Sn$	α	0.29 ± 0.02	0.71 0.77
15.6 MeV/u $^{16}O+^{116}Sn$	p	1.08 ± 0.09	2.98
15.6 MeV/u $^{16}O+^{116}Sn$	α	0.39 ± 0.03	2.03
4.7 MeV/u $^{64}Ni+^{68}Zn$	p	0.22 ± 0.02	1.27
4.7 MeV/u $^{64}Ni+^{68}Zn$	α	0.23 ± 0.02	0.87
6.3 MeV/u $^{64}Ni+^{68}Zn$	p	0.48 ± 0.05	1.98
6.3 MeV/u $^{64}Ni+^{68}Zn$	α	0.47 ± 0.05	1.66
7.8 MeV/u $^{64}Ni+^{68}Zn$	p	0.47 ± 0.05	2.63
7.8 MeV/u $^{64}Ni+^{68}Zn$	α	0.48 ± 0.05	2.32

Inadequacy of the statistical model = E. Vardaci et al., Eur. Phys. J. 43(2010)127

Evaporative emission (Future)

LETTER OF INTENT

Measurements of level densities from compound nuclear reactions

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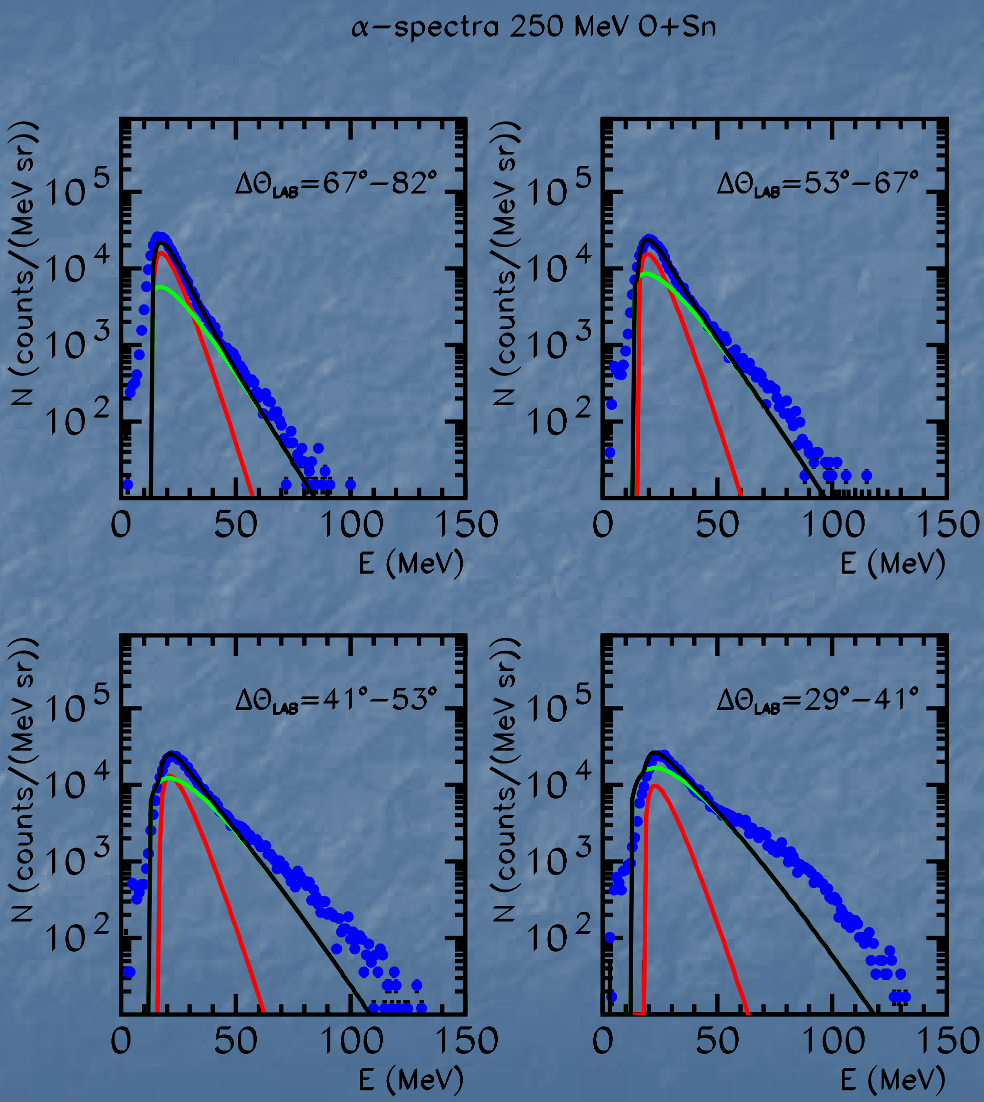
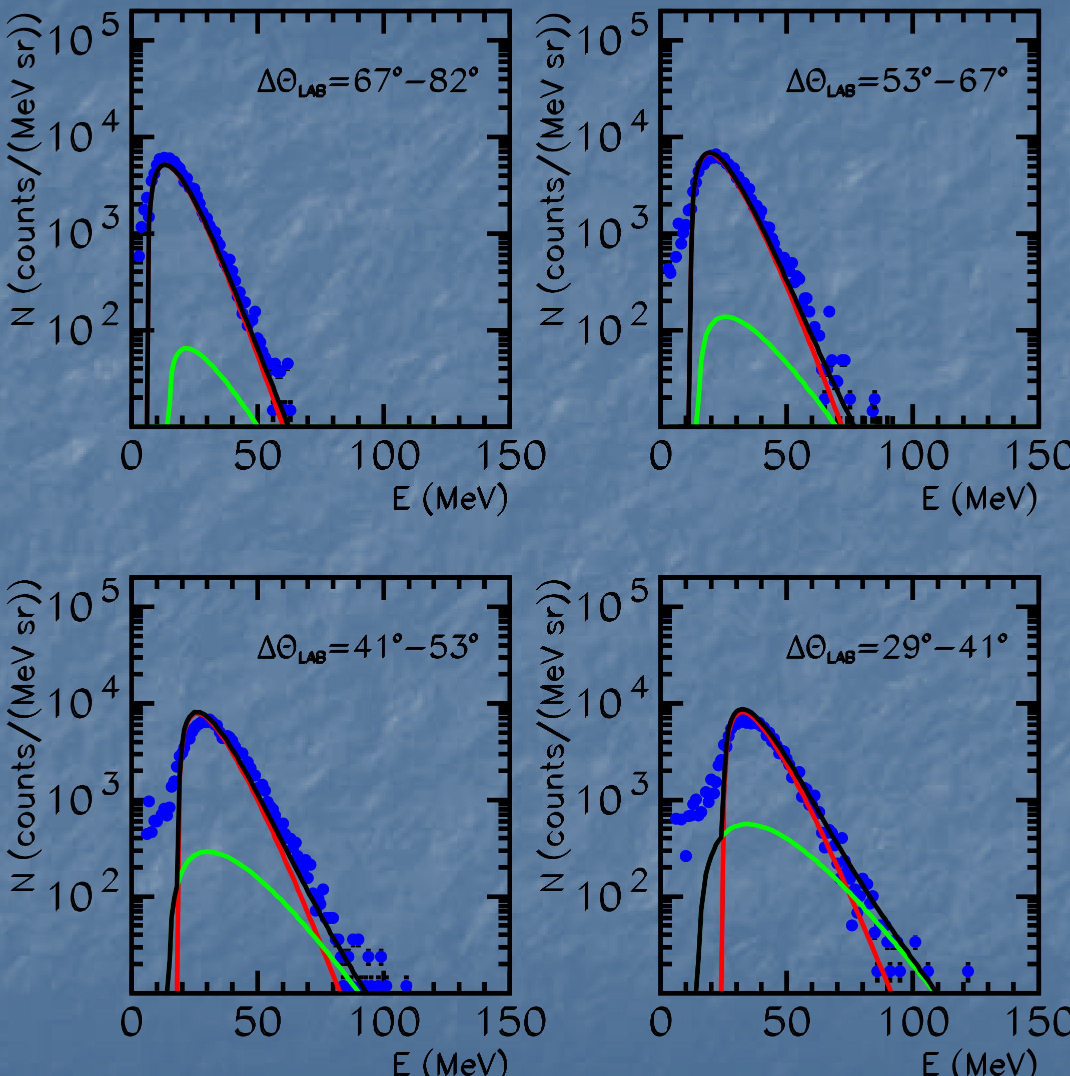
Abstract

We propose to measure the level density of nuclei of medium-light mass region, for excitation energies up to ~ 25 MeV, using as a probe the light particles emitted in fusion evaporation reactions. The main objective is twofold: i) to collect high quality experimental data on level density in the whole proposed range of excitation energy, data which are missing in the literature. This will allow to test the current models and to extract a more precise level density parameterization. ii) to study the behavior of the level density when going gradually away from the stability line, this work being important for future experiments with SPES facility We intend to perform experiments at LNL with Tandem beams, using GARFIELD, 8πLP, and RIPEN experimental set-ups in order to measure high precision evaporative light particle energy spectra and angular distributions. Following a well established method, the level density of specific nuclei can be measured as a function of the excitation energy, from the high energy side of the particle energy spectra, which is expected to arise mainly from the first step emission. At the same time, the whole energy spectrum, which includes the contribution from all the steps of the evaporative chain, is expected to be astringent test for the level density models.

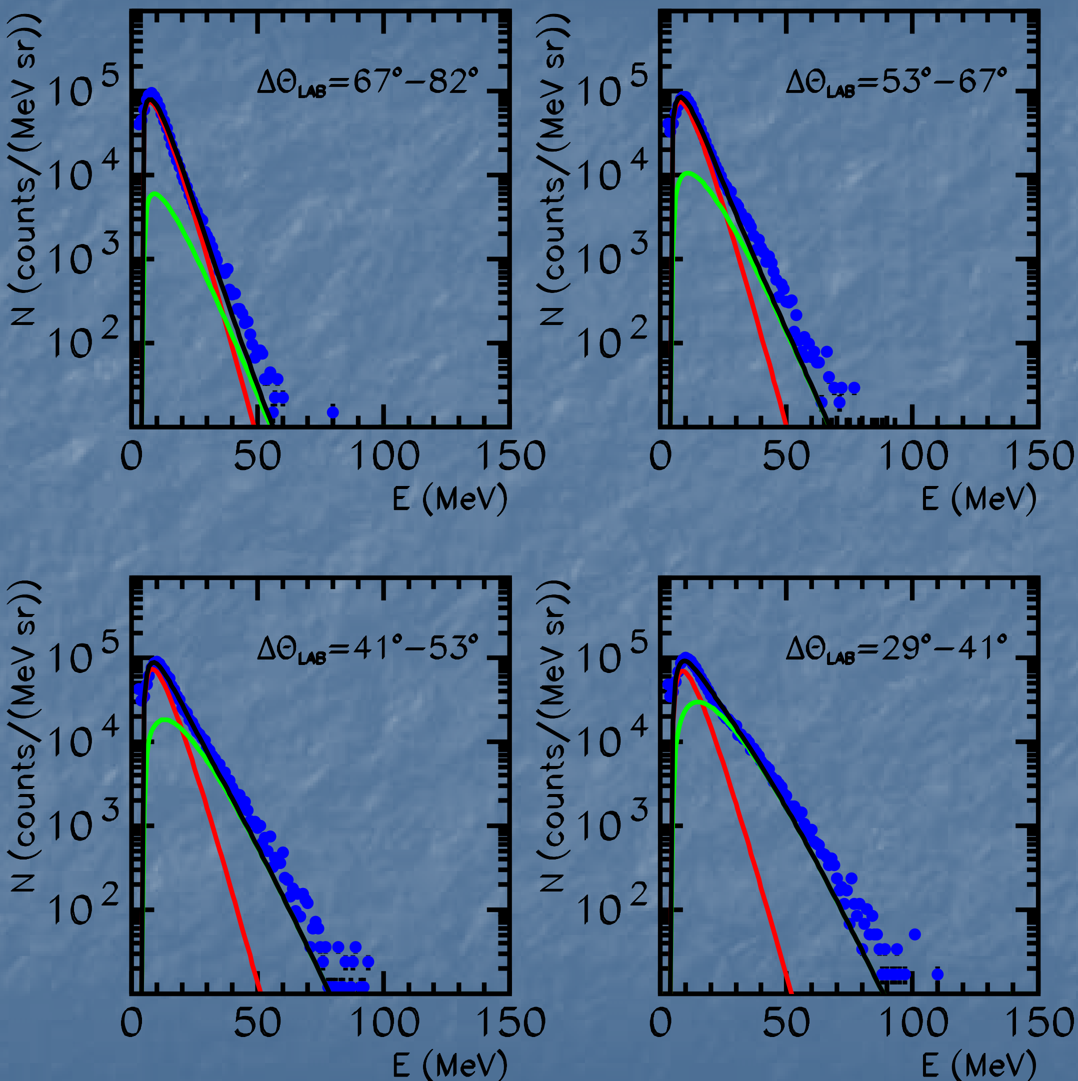
Part 2. Pre-equilibrium emission (Past)



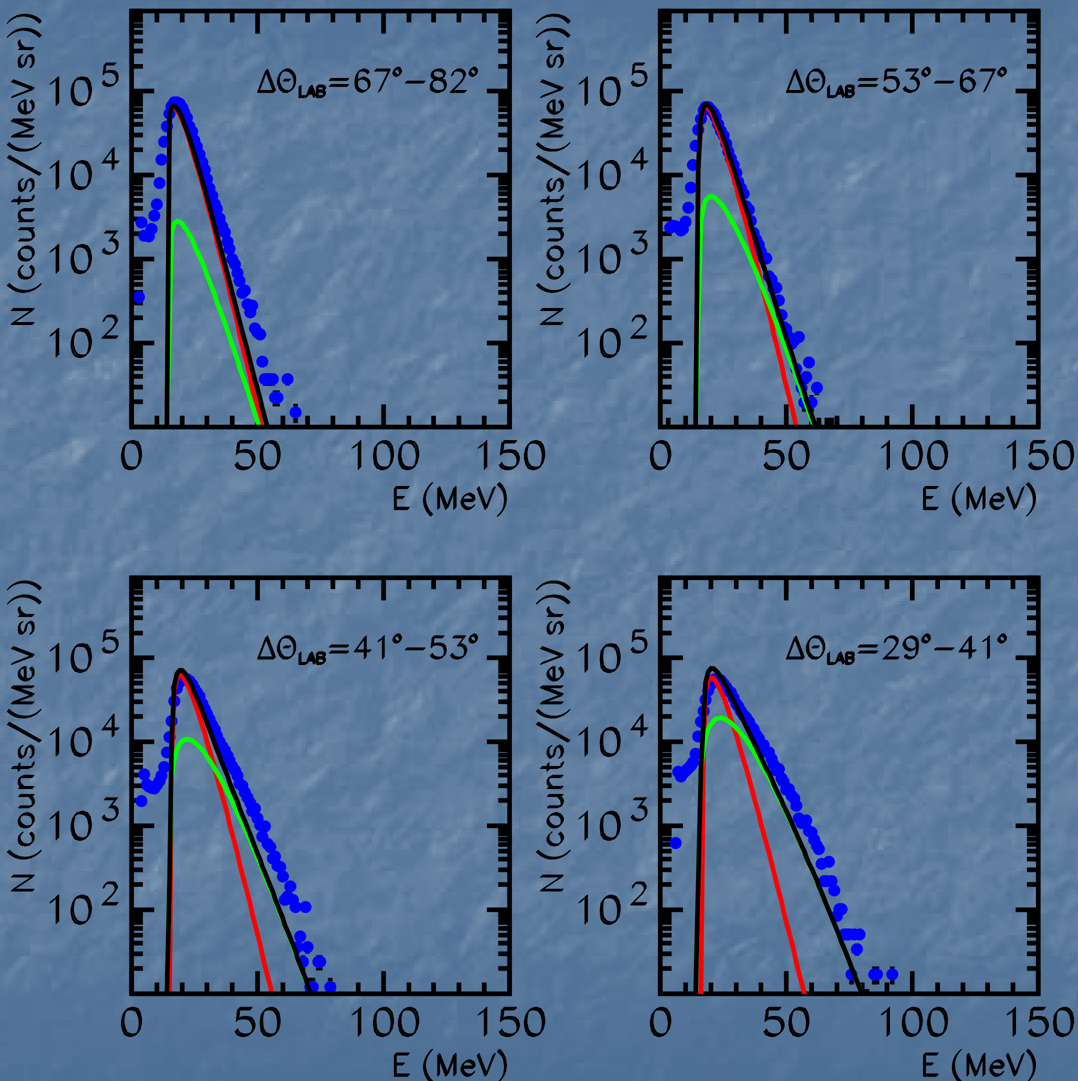
α−spectra 500 MeV Ni+Zn



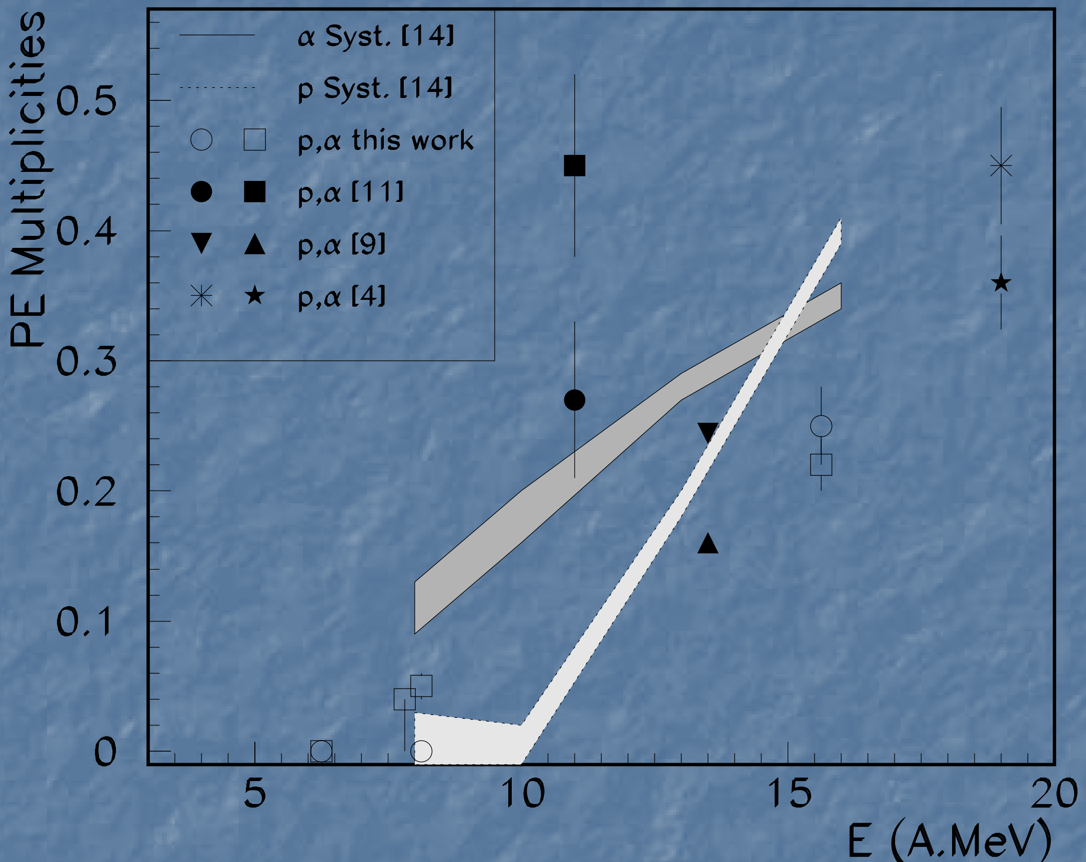
p−spectra 250 MeV O+Sn



α−spectra 130 MeV O+Sn



Results



14 - J. Cabrera *et al*, Phys. Rev. C **68**, (2003) 034613
11 – M. P. Kelly *et al*, Phys. Rev. C **56**, (1997) 3201
9 – D. Prindle *et al*, Phys. Rev. C **48**, (1993) 291
4 – K.A. Griffoen *et al*, Phys. Rev. C **37**, (1988) 2502

Reaction	LCP	N_2/N_1	M^{PE}
8.1 MeV/u $^{16}O+^{116}Sn$	α	0.21	0.05 ± 0.01
15.6 MeV/u $^{16}O+^{116}Sn$	p	0.30	0.25 ± 0.03
15.6 MeV/u $^{16}O+^{116}Sn$	α	1.30	0.22 ± 0.02
7.8 MeV/u $^{64}Ni+^{68}Zn$	α	≤0.10	≤0.04

E_{BEAM} MeV/u	Reaction	M_{LOSS}^{PE}	Z_{LOSS}^{PE}
7.8	$^{64}Ni+^{68}Zn$	0.39 ± 0.15	0.08 ± 0.01
8.1	$^{16}O+^{116}Sn$	0.43 ± 0.16	0.10 ± 0.02
15.6	$^{16}O+^{116}Sn$	2.08 ± 0.26	0.69 ± 0.05

E_{BEAM} MeV/u	Reaction	E* MeV	E_{LOSS}^{PE} %
7.8	$^{64}Ni+^{68}Zn$	203	3.6 ± 2.0
8.1	$^{16}O+^{116}Sn$	100	5.6 ± 2.9
11.1	$^{18}O+^{100}Mo$	174	21.4 ± 2.6
13.0	$^{20}Ne+^{169}Tm$	197	12.7 ± 1.5
13.0	$^{20}Ne+^{159}Tb$	201	13.9 ± 1.5
15.6	$^{16}O+^{116}Sn$	206	19.9 ± 3.4
16.0	$^{20}Ne+^{169}Tm$	251	15.9 ± 2.4
16.0	$^{20}Ne+^{159}Tb$	254	18.5 ± 2.4

Memory of the entrance channel !

THEORY

Model calculation (Unified Code, O.V. Fotina, Moscow State University)

Evaporative (statistical) emission:

The method of analysis of heavy-ion reactions is based on the statistical theory of nuclear reactions using Monte-Carlo simulation of a number of characteristics of nucleus disintegration (modified PACE2 code):

- decay channel (n, p, alpha, gamma or fission);
- kinetic energy of escaping particles;
- particle escaping angels, and (or) angular momentum of emitting particles.

Probabilities of all process were estimated within Hauser-Feshbach model

Pre-equilibrium emission :

- To describe the relaxation processes in the nuclear system produced in the investigated fusion reaction Hybrid exciton model based on Griffin exciton model was used {J.J. Griffin, Phys. Rev. Lett., **478**, p 478 (1966)}.
- In the Hybrid exciton model, the state of the nuclear system produced by collision of bombarding particle and target nucleus is determined by the exciton number $n = p + h$, where p is a number of particles located above the Fermi energy and h is a number of holes located under the Fermi energy, and by excitation energy E^*.
- More detailed description of using method was done in D.O.Eremenko, O.V. Fotina, et al. Phys. of Atomic Nuclei, Vol. 65, No 1, 2002, pp 18-37
- We regard as free parameter next values ***n, k, g.***
  - ✓ k is parameters, connected with transition matrix element $<|M|^2>$ and determined of the transition rate of emission particle into continuum with energy ε_b. This parameter was varied in wide region from 200 to 800 MeV^3.
  - ✓ The single particle level density g is connected with the level density parameter in the Fermi-gas model by relation $g = 6a/\pi^2$. For variation of values g we used Fermi-gas model and level-density phenomenological model {A.V. Ignatyuk, K.K. Istekov, and G.N. Smirenkin, [Yad. Fiz., **29**, 875 (1979)] Sov. J. Nucl. Phys. **29**, 450, 1979
  - ✓ And n is mentioned above exciton number. The initial exciton configuration (p_0, h_0) from which the equilibration process starts is the free parameter of the model. In our calculations we used next of the initial exciton configurations: n_0 **= (16p,0h) ($^{16}O+^{116}Sn$); n_0=(64p,1h) ($^{64}Ni+^{68}Zn$)**.

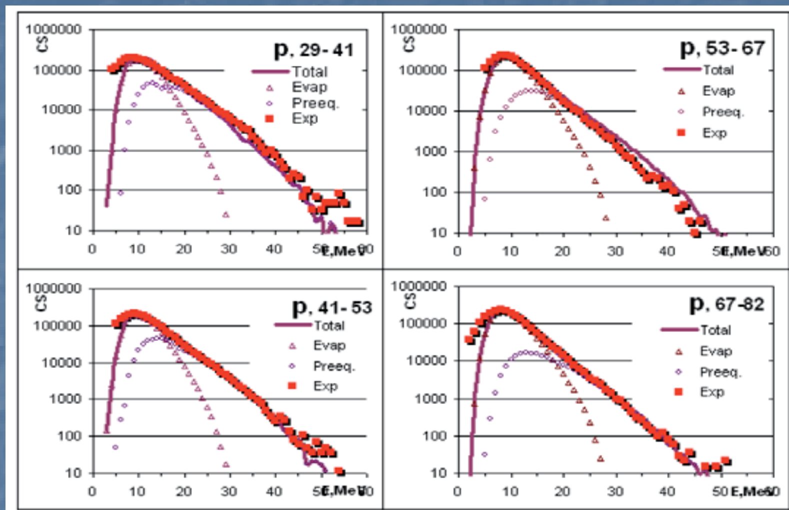
Probability of α-particle pre-formation in projectile nucleus:

α-particle spectroscopic amplitudes within the SU(3) model

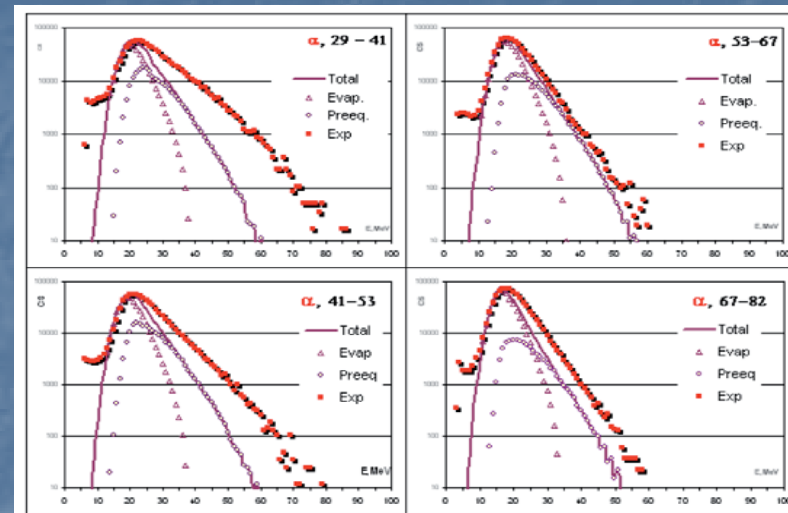
Model calculations (preliminary)

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

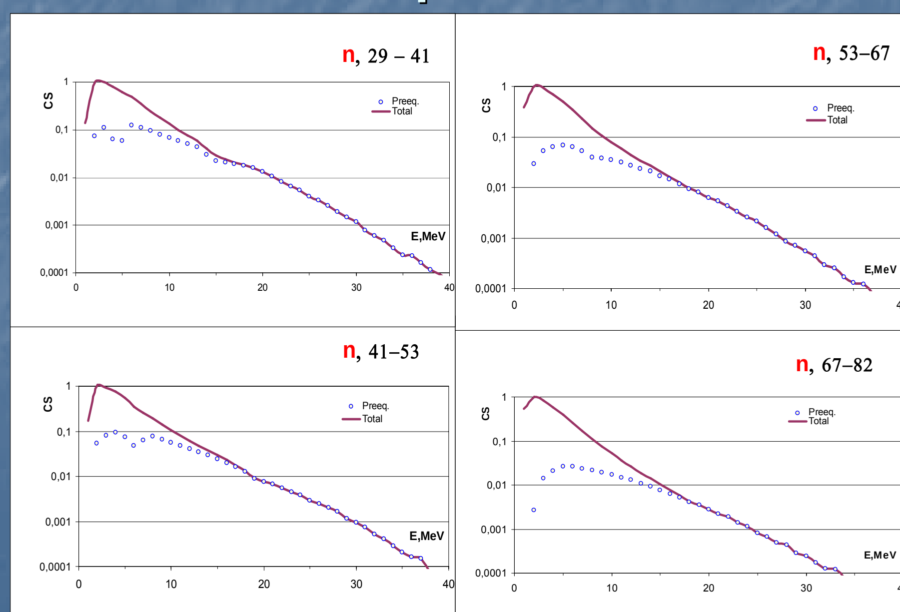
p spectra



α spectra

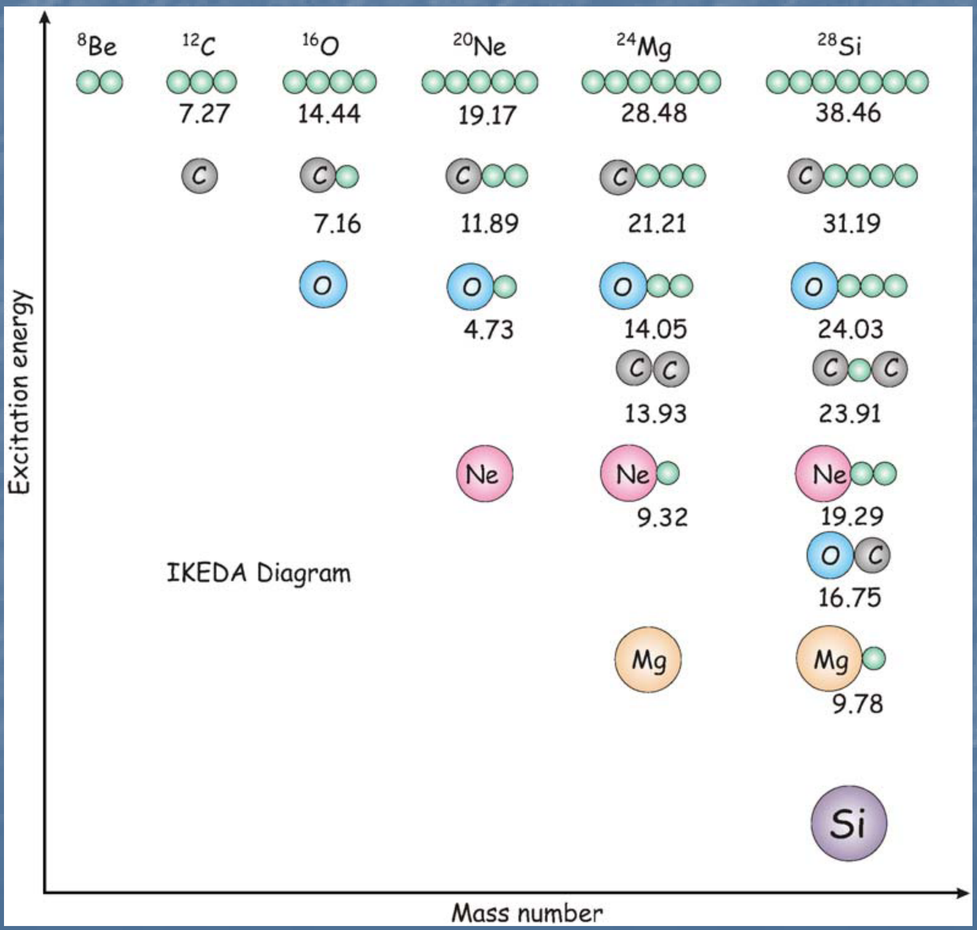


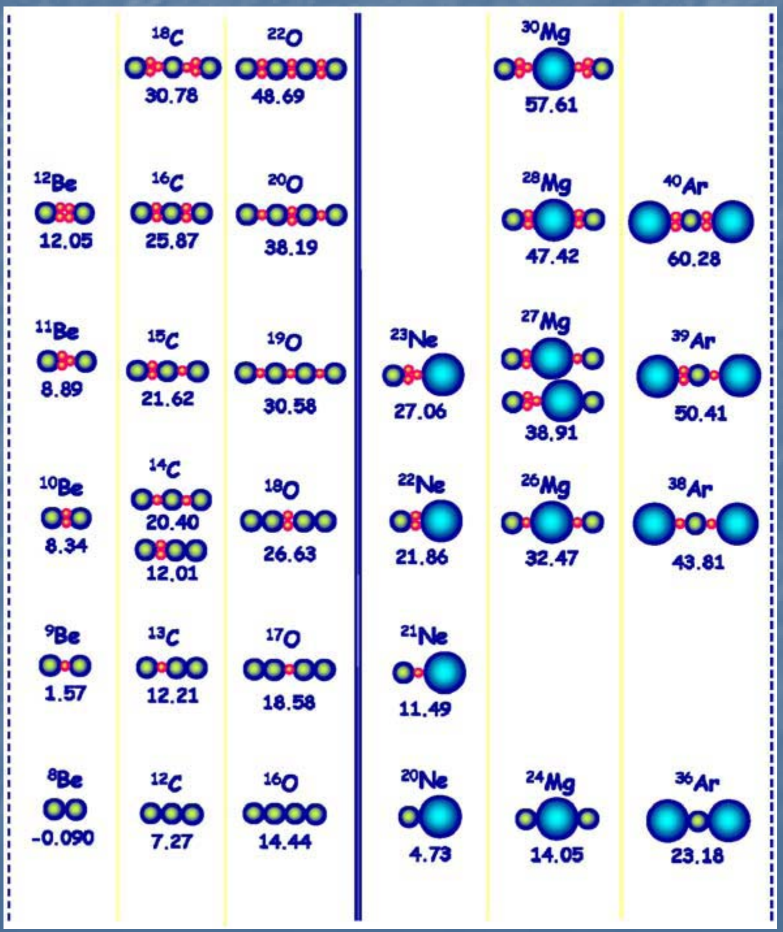
n spectra



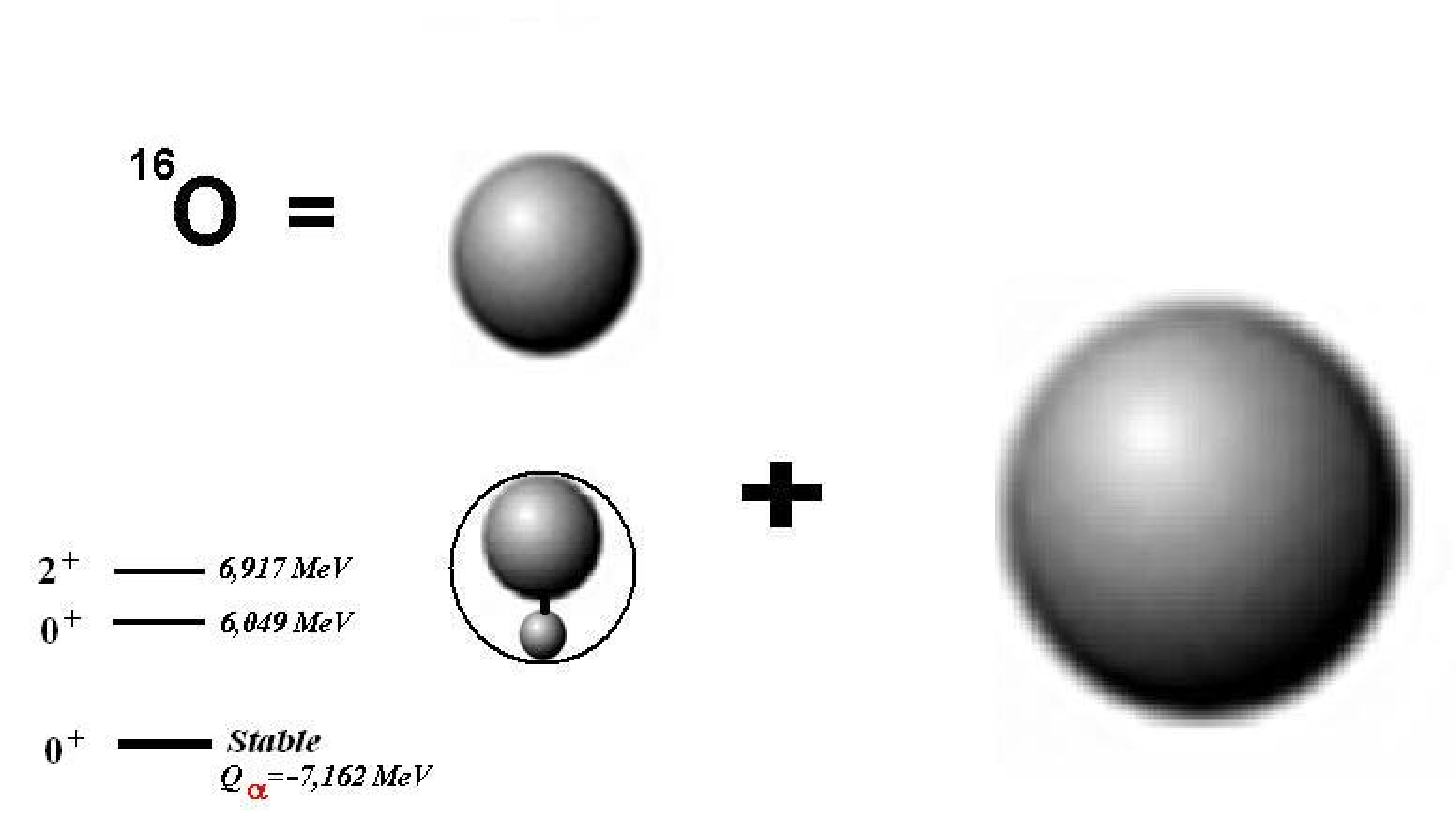
Part 3. Alpha clustering in nuclei

IKEDA DIAGRAMS





Possible α clustering configurations in ^{16}O nucleus
simplified case



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B. Buck, A.C. Merchant, S.M. Perez, Phys. Rev. C, 45, 2247 (1992)
M. Ichimura, A. Arima, Nucl. Phys. A204, 225,(1973)
Yu.A. Berezhnoy, V.P. Mikhailyuk, Phys. Elem. Part and Nucl., 39, 437, (2008)

Alpha clustering study using pre-equilibrium emission as a probe (Future)

<u>Tandem-Alpi proposal</u>: ACLUST-GARFIELD

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

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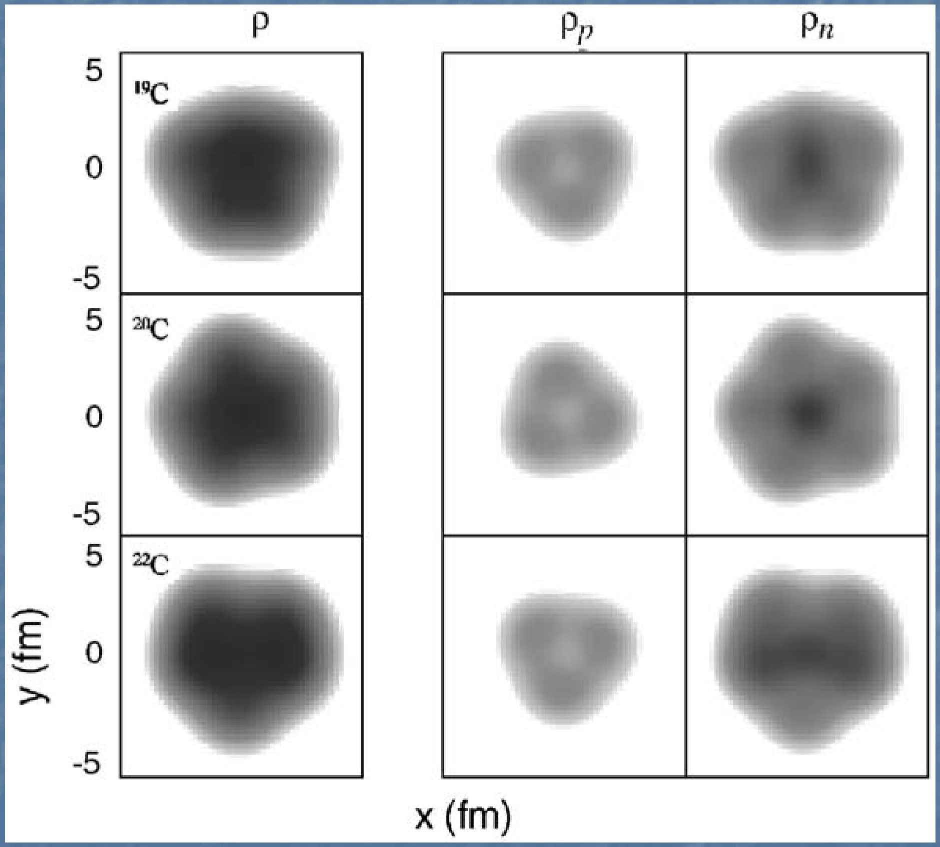
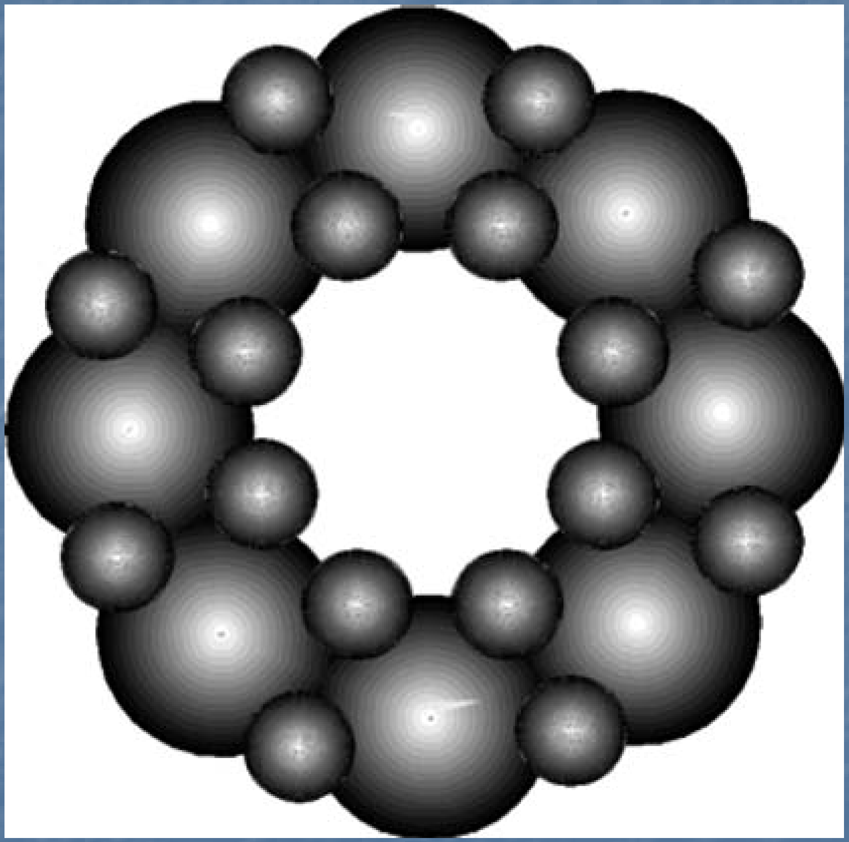
ABSTRACT

We propose to investigate the alpha-particle emission from hot 81Rb nucleus, formed in the reactions with alpha-cluster 16O projectile on 65Cu target and with non alpha-cluster 19F projectile on 62Ni target, using the GARFIELD and RCo detector arrays. The main goal of the proposal is to measure the pre-equilibrium alpha-particle emission for the two systems indicated above in order to extract information about the influence of alpha-clustering in the 16O projectile on productions of alpha particles during the non-equilibrium stage of the nuclear reactions. Experimental study of the effect is a perspective way for investigation of alpha clusterization in exotic neutron rich nucleus. We propose to study two cases. In the first one the projectile energy per nucleon will be the same: 16 MeV/u for the 16O and 19F beams. In the second case the composite system formed in the same two reactions will have the same excitation energy of 209 MeV. The total request of beam time is 10 days (not including tuning of ALPI). 1 pnA pulsed beams with a resolution of 1 ns and a repetition time of 400 ns (or 800ns depending on the accelerator performances) is required. Targets, 65Cu and 62Ni, will be 0.5 mg/cm2 thick each.

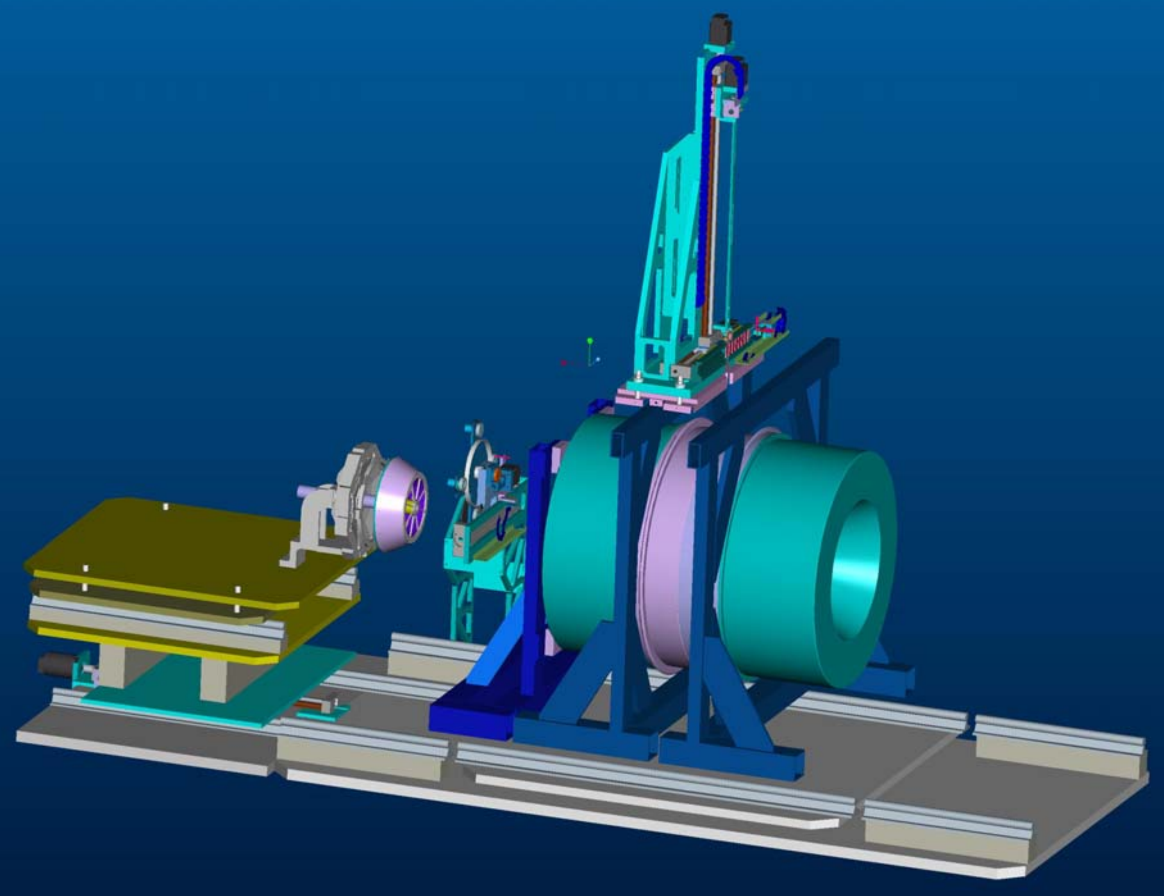
FUTURE PERSPECTIVES:

FLOWERS, RINGS AND MANY MORE TOWARDS RADIOACTIVE BEAM FACILITIES





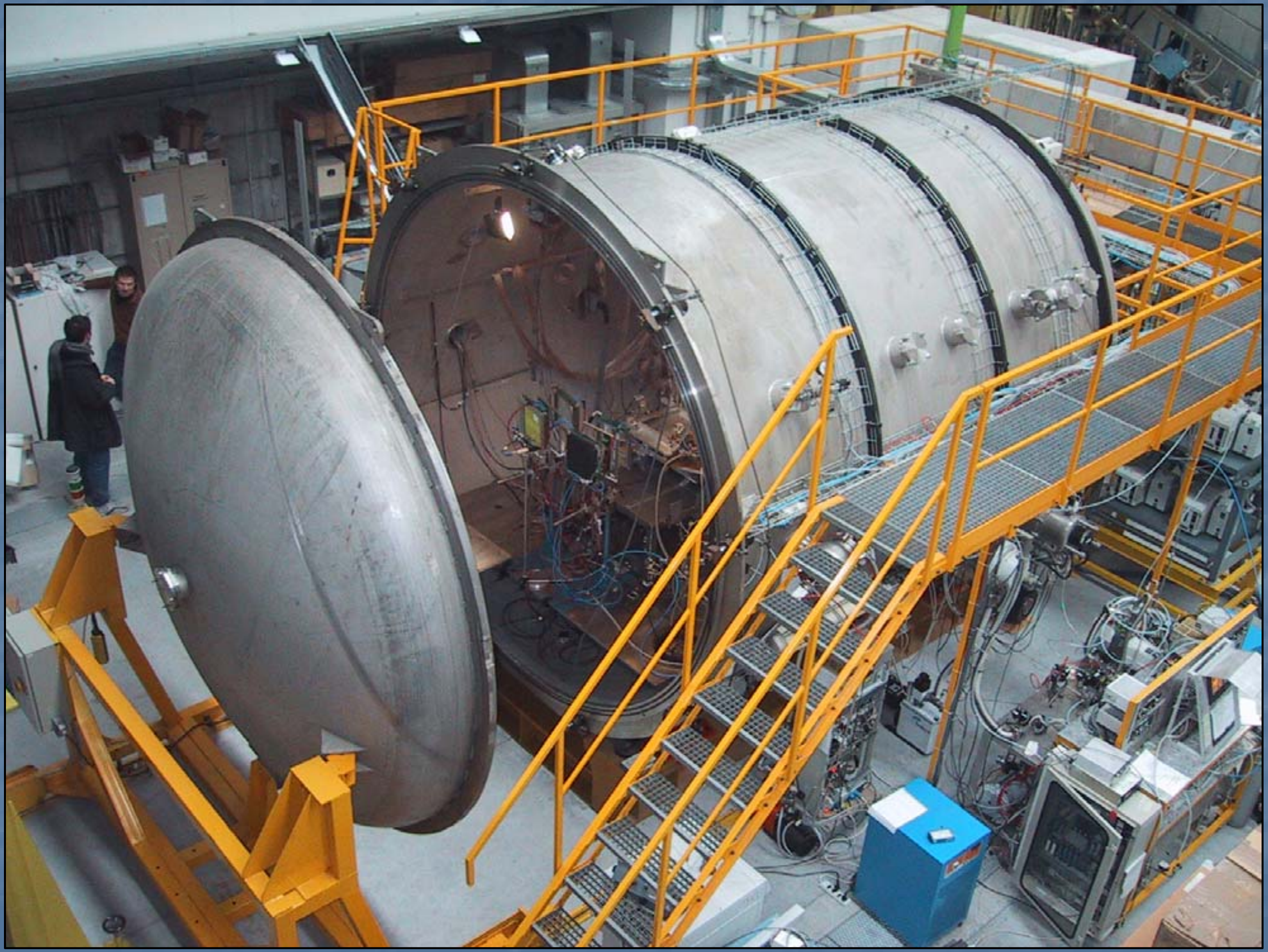
GARFIELD-RCo Experimental Setup



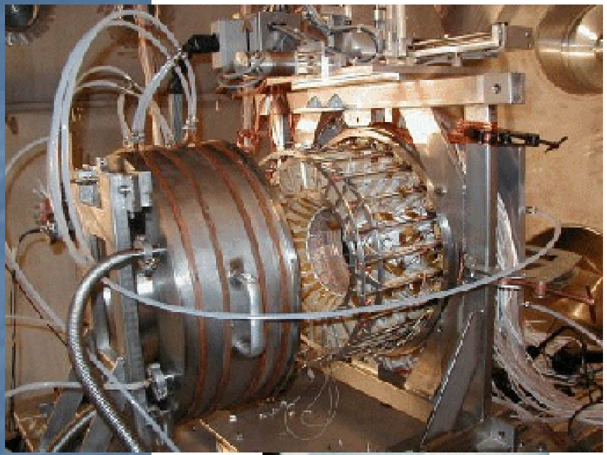
GARFIELD+RCo Setup

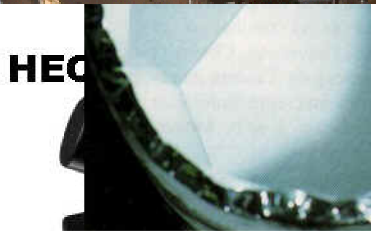
G. AR. F. I. E. L. D.

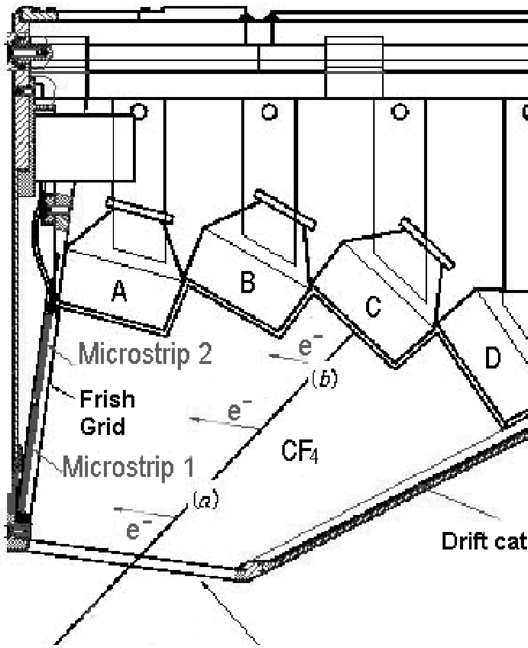
General ARray for Fragment Identification and for Emitted Light particles in Dissipative collisions

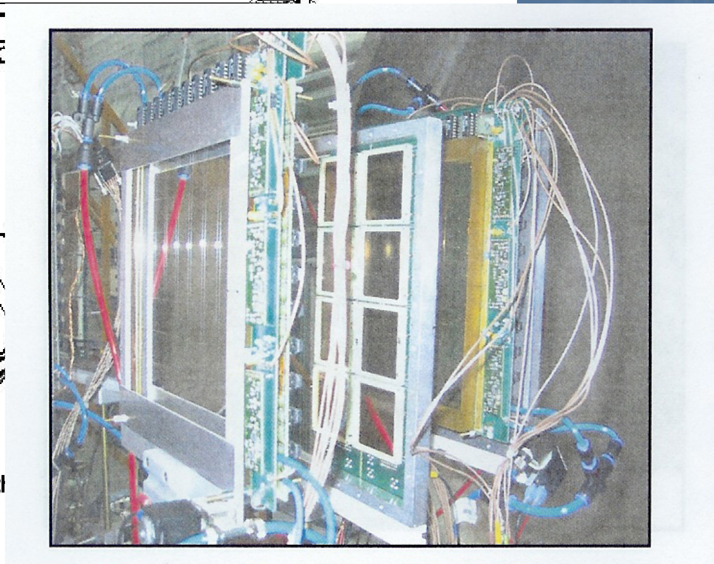


Experimental setup









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GARFIELD - 4π complex multidetector apparatus for particle detection

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-Identification threshold is 0.9 MeV/u

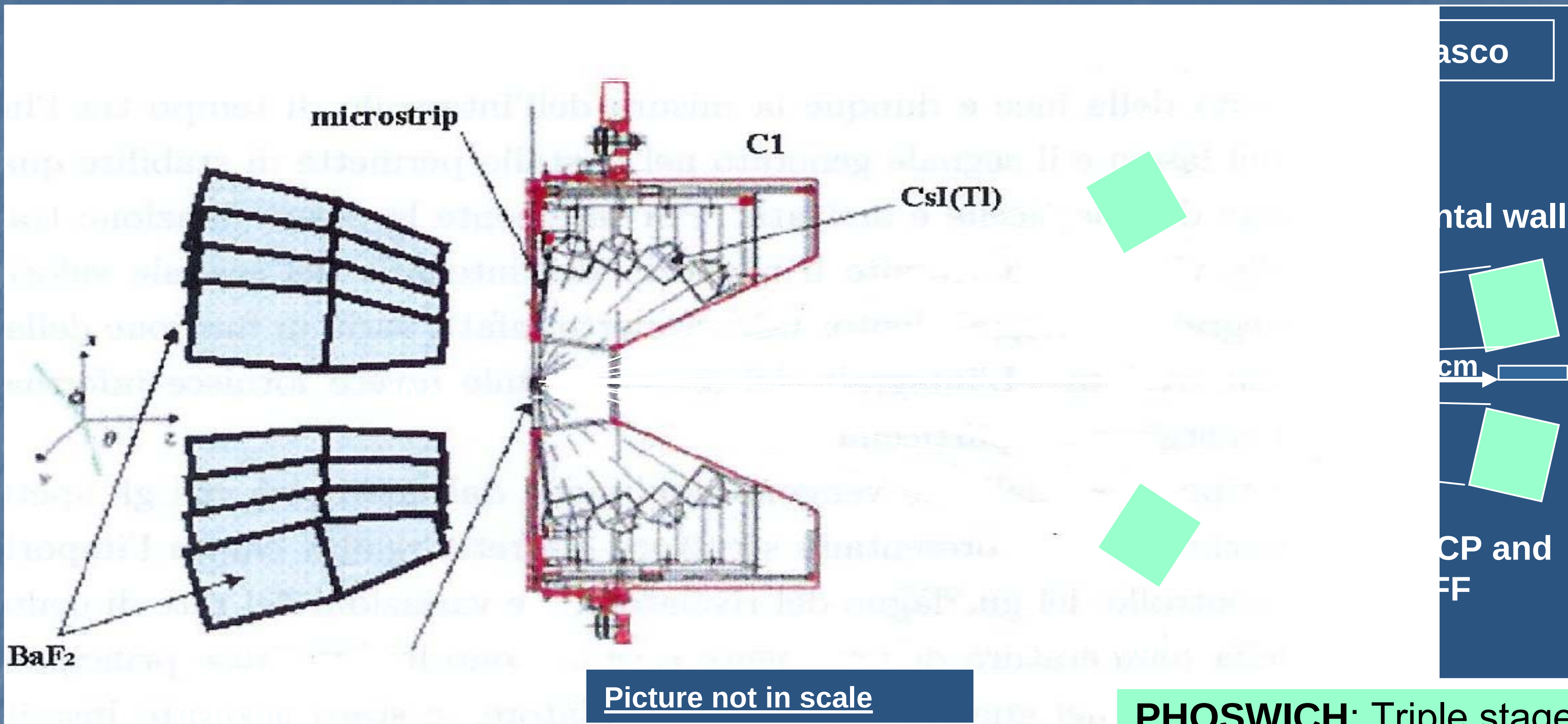
Two couples of PSPPAC's were used for the Evaporation Residues detection covering the angular range 4°-12°.

-Time resolution is 800 ps

-Detection efficiency is around 100% for Z>10

-The active area is 20X20 cm^2

Experimental set-up



HECTOR: 8 large BaF_2 crystals used for the detection of high energy γ-rays

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

In the experiment the angular coverage was 30°- 90° in θ and 2π 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

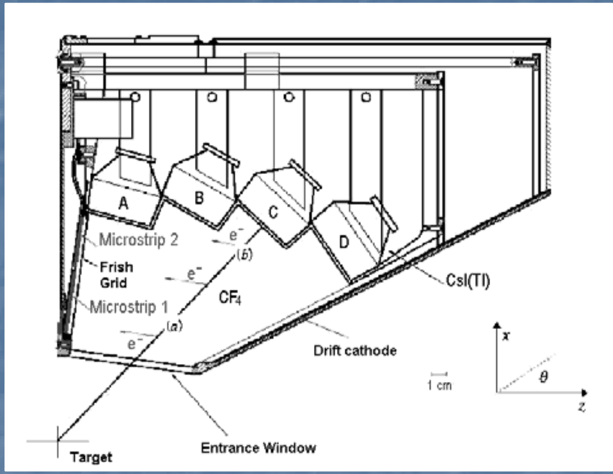
PHOSWICH: Triple stage (Plastic-Plastic-CsI(Tl)) telescopes

Angular coverage from ~6° up to ~12° in θ (near π in φ) for the frontal wall) and ~13° up to ~20° in θ (lateral box)

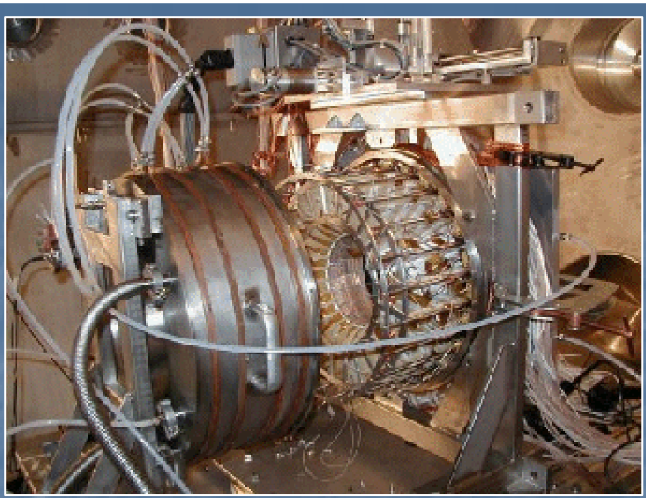
Charge resolution from Z=1 to Z=12. p,d,t separation in CsI(Tl)

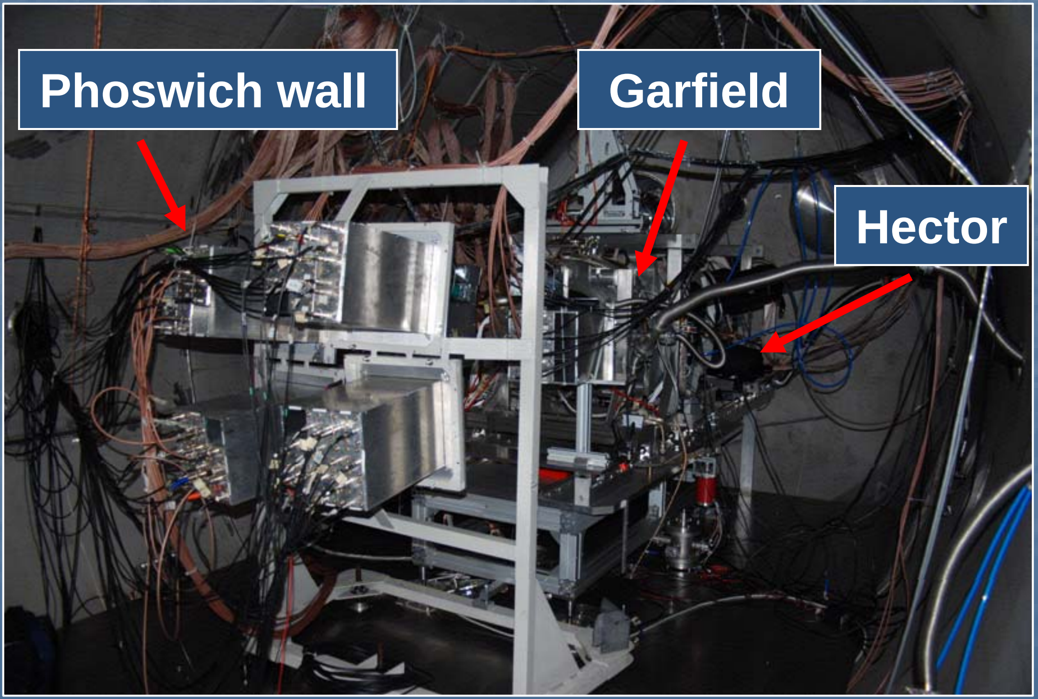
Experimental set-up

The GARFIELD detector:



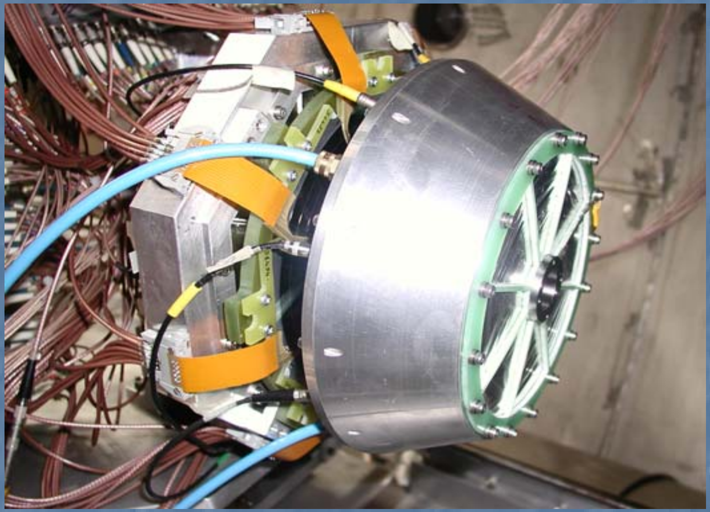
Scheme of a drift sector in Garfield





Experimental set-up

The Ring Counter (RCo) detector:



RCo: A high resolution IC-Si-CsI(Tl) ΔE-E telescopes.

The angular coverage is 3.5°- 17.5° in θ corresponding to a solid angle ≈0.27 sr.

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.

Moving source analysis

1) Evaporative (statistical equilibrium) contribution

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

2) Pre-equilibrium contribution

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

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

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

Conclusion

- The Light Particle emission mechanisms were studied for the heavy-ion reactions in the beam energy range 5-20 MeV/u with different mass-asymmetries at the entrance channel for:
  a) the same compound systems and E*,
  b) the same projectile energy.

- A strong dependence of the pre-equilibrium emission on the projectile energy is confirmed.

- Evidences of the dependence of the pre-equilibrium emission on the reaction entrance channel mass-asymmetries were found.

- Experimentally obtained pre-equilibrium particle multiplicities and CN energy losses follow a systematics of J. Cabrera *et al*, Phys. Rev. C **68** (2003) 034613.

- This work stimulated development of the unified model for a simultaneous description of the evaporative statistical and fast pre-equilibrium particle emission mechanisms.

Outlook

- New experimental data are needed in the case of mass-symmetric entrance channel heavy-ion reactions for the higher projectile energies (~15 MeV/u), where pre-equilibrium contribution is significantly large. A good candidate is 15.6 MeV/u $^{64}Ni+^{68}Zn$ reaction.
- Measurement of the pre-equilibrium neutron spectra will provide a significant contribution for the development of the theoretical models.
- Study of the alpha-clustering structure could be performed by measuring two systems with alpha-clustered (a good candidate is 17-18 MeV/u ^{16}O) and non-alpha-clustered (a good candidate is 17-18 MeV/u ^{19}F) projectiles leading to the same Compound Nucleus with the same excitation energies.
- Study of the isospin effects in the heavy-ion reactions in the projectile energy range from 15 to 20 MeV/u.
- Continue the work in the research line concerning the development of the Griffin exciton model in a convolution with an evaporative statistical code

NUCL-EX – HECTOR Collaboration

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Model calculation

- In the frame of Griffin model we estimate particles ejections probabilities and the energy spectra of particles (n, p, α).

- Then using Monte-Carlo simulations we obtain kind of pre-equilibrium particle (n or p or α) with its energy

- Using optical model we determine the angular momentum of the emitting particles

- And (using calculations of associated Legendre functions) we select the particles ejection's angle.

- Monte-Carlo method is used to determine angular momentum J_f (projectile + target) (ordinary PACE procedure) and then one obtains the angular momentum of the equilibrium Compound Nucleus $J_f+J_p \geq J_c \geq |J_f-J_p|$

Model calculation

Master equation in the Griffin exciton model:

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

Generalized master equation :

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

Free differential nucleon-nucleon scatteing cross-section:

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

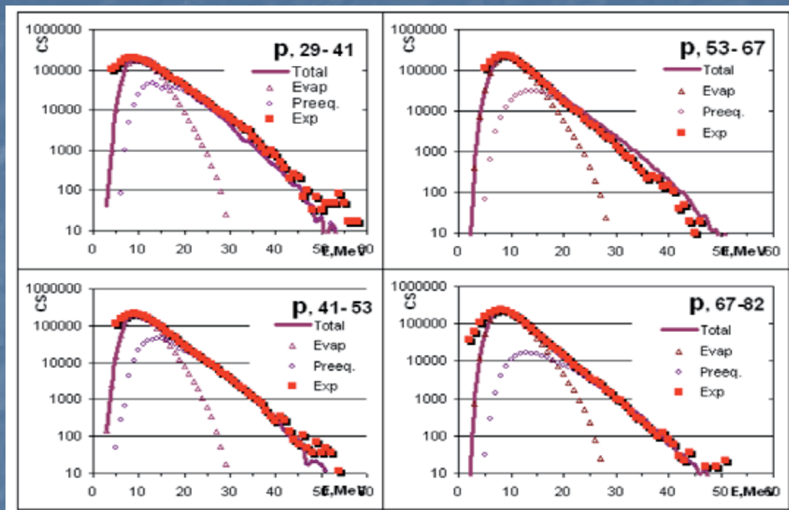
Initial condition:

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

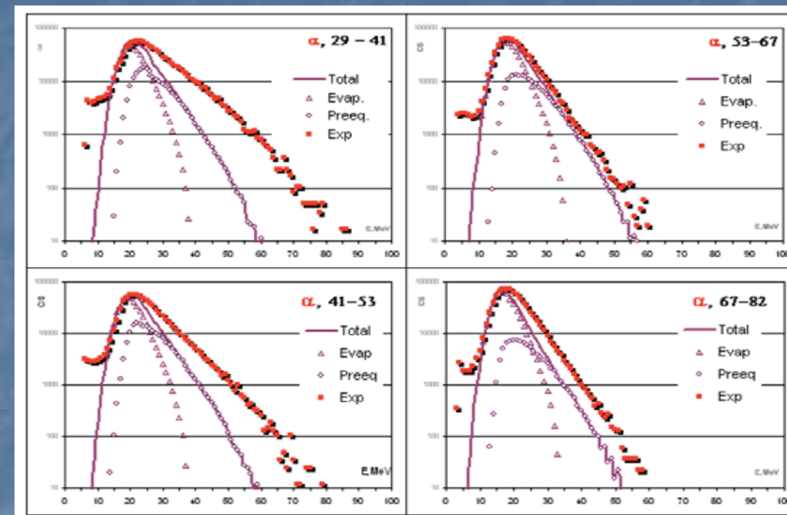
Model calculations

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

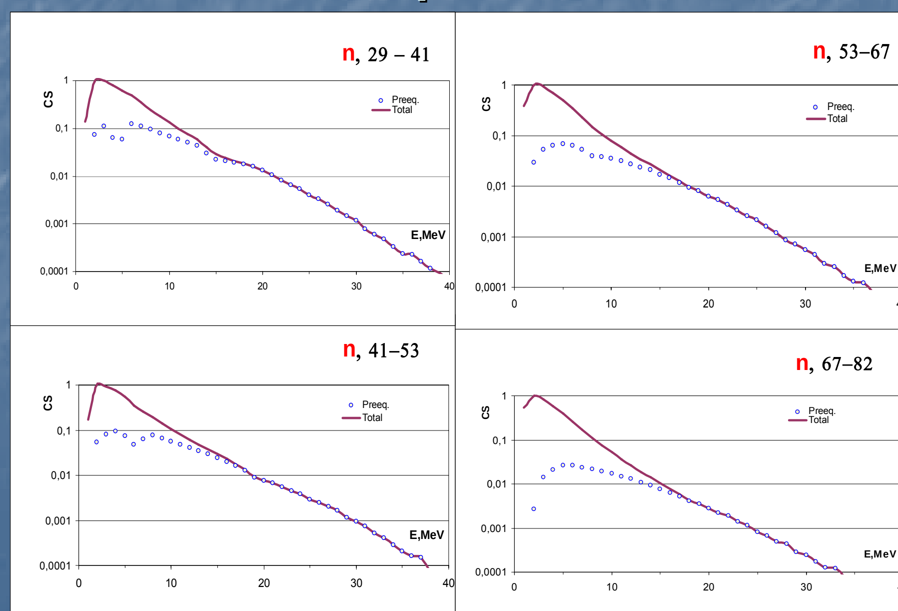
p spectra



α spectra



n spectra



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