Alpha-particle clustering in excited expanding self-conjugate nuclei

$^{40}Ca+^{12}C$, 25 AMeV with CHIMERA multidetector

Motivations: theoretical calculations predict that at low density alpha-conjugate nuclei spontaneously cluster into alpha-particles

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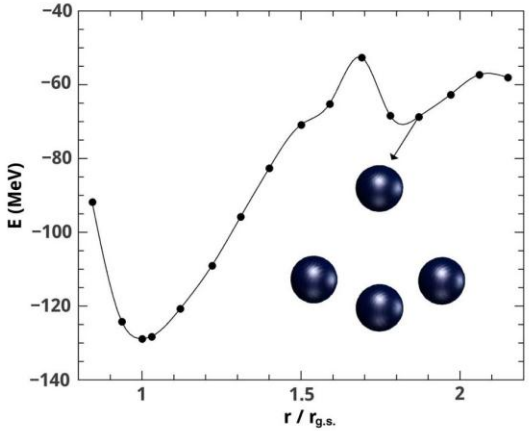
Constrained Hartree-Fock-Bogoliubov approach ^{16}O, ^{20}Ne …
Deformation-constrained self-consistent relativistic Hartree-Bogoliubov (RHB) model



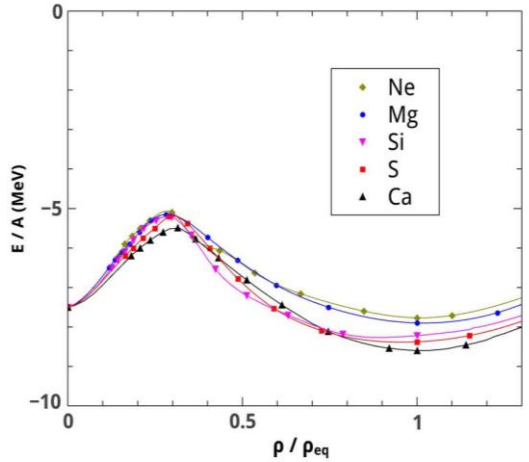


FIG. 5 (color online). Equation of state for a choice of self-conjugate nuclei (EOS-A) as a function of average density scaled by the one at equilibrium; see text for detailed definition.

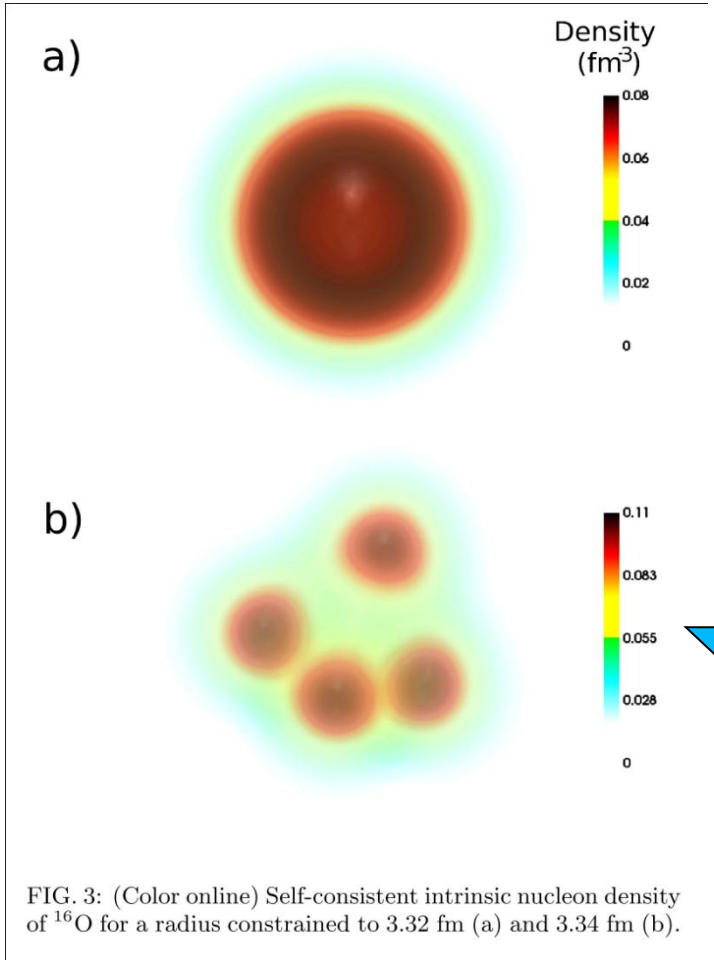


FIG. 3: (Color online) Self-consistent intrinsic nucleon density of ^{16}O for a radius constrained to 3.32 fm (a) and 3.34 fm (b).

$r/ r_{g.s.} \approx 1.3$

M. Girod and P. Schuck, PRL 111 (2013) 132503

J.-P. Ebran et al., PRC 89 031303(R) 2014

Experimental strategy

We search for a possible simultaneous emission of alpha-particles from excited expanding alpha-conjugate nuclei

intermediate energy HI reactions to possibly produce some hot expanding projectile fragmentation products

➔ $^{40}Ca + ^{12}C$ at 25 MeV per nucleon

associated with high detection granularity (CHIMERA) to precisely reconstruct velocity vectors

Well known that around 25-30 AMeV incident energy fragmentation of ^{20}Ne projectiles is dominated by alpha-conjugate fragmentation products ^{16}O, ^{12}C…

M. Morjean et al., NPA 438 1985 547

CHIMERA experiment

Beam intensity: 10^7 ions/s

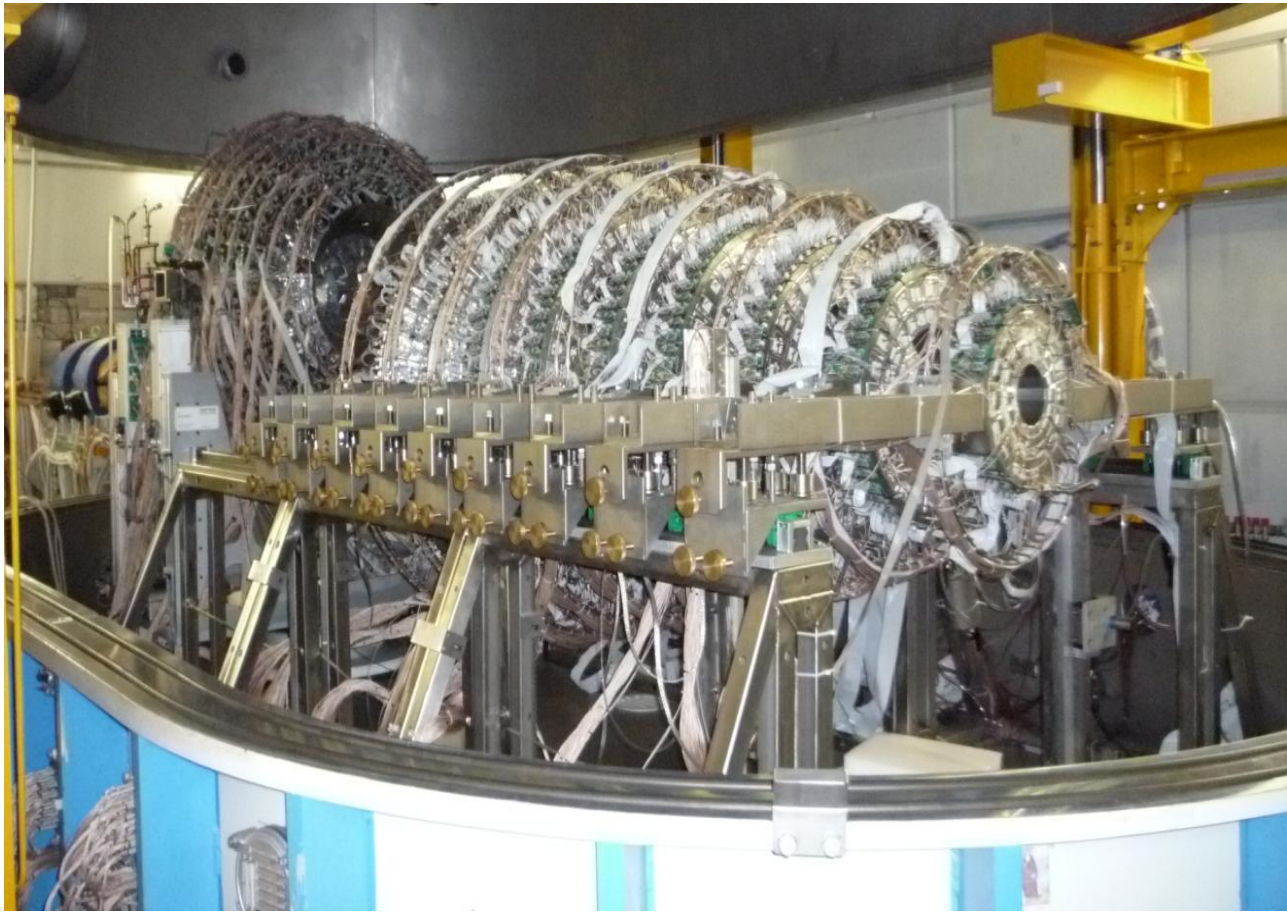
thin target 320μg/cm^2

Angular range used: Θ=1-62°

=> 816 telescopes

Si ≈ 200-300 μm

CsI(Tl) from 12 to 3 cm



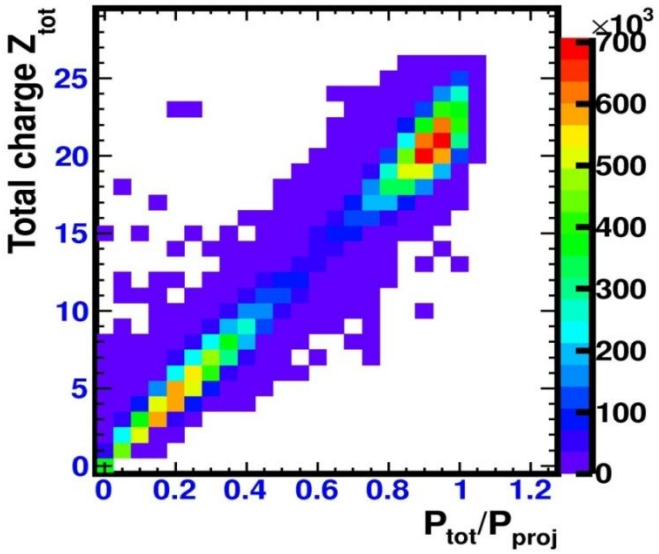
Identification in Z and A

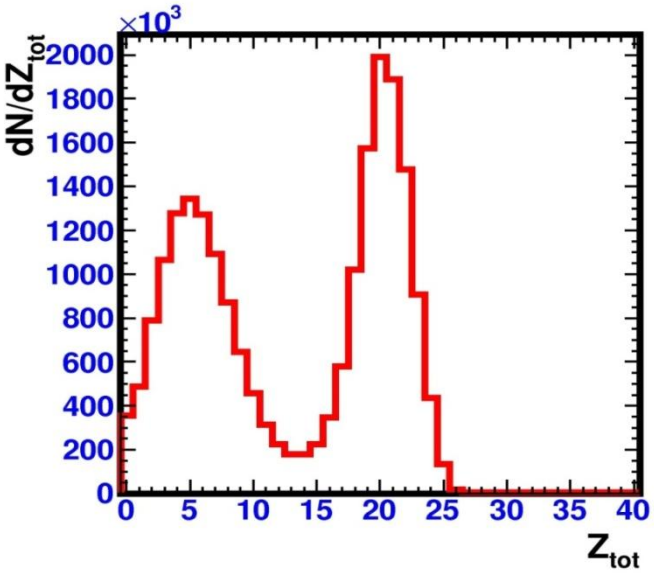
for the energy range of interest

alpha-particles: dedicated energy calib. of CsI(Tl) from time of flight - energy resolution 1-2.5%

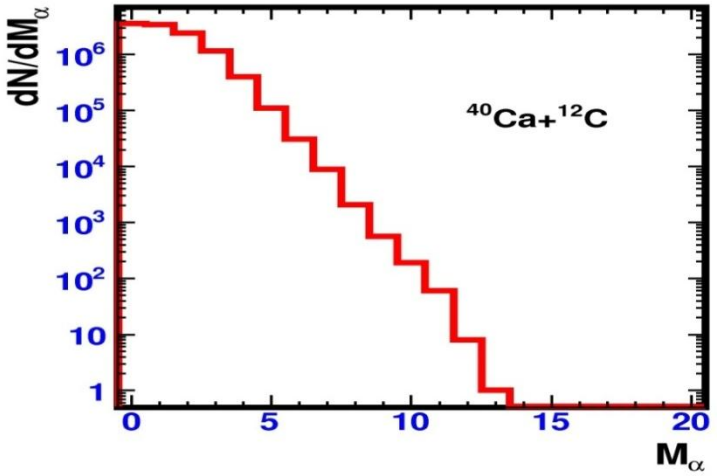
Overview of event reconstruction/identification

grazing angle = 1.11° - ring 1I (1.0°-1.8°) suppressed





$Z_{tot} \geq 19$



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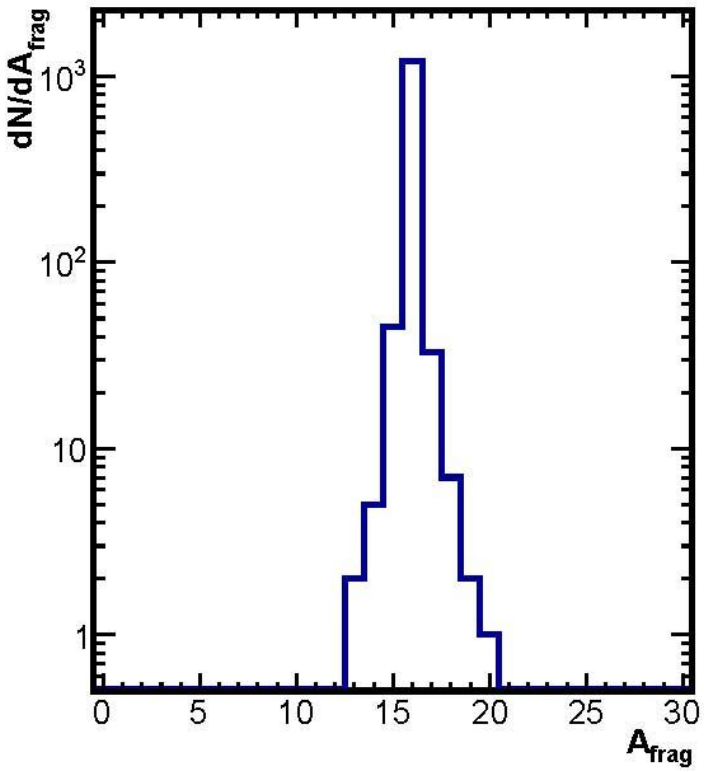
Selected mechanism – Proj. Frag. (PF) Z_{tot}=20
Selected events: (M_{alpha}=4,5,6) + only 1 frag.(Z_{frag}=20-2xM_{alpha})

distribution of A_{frag} for
Z_{frag}=8 and M_{alpha}=6

neutron transfers-less than 5%



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M_{alpha} => Na system ?

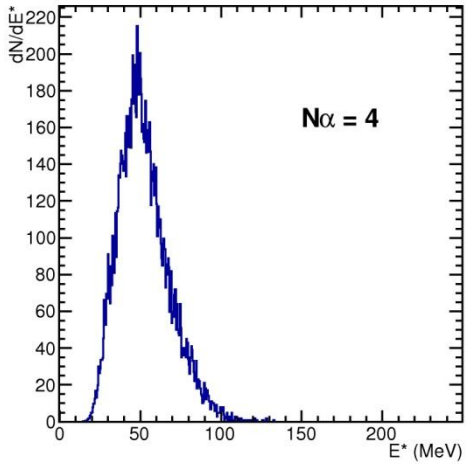
Some α-particles from preequil.
Some α-particles from $^{12}C^*$, $^{16}O^*$
either fragments or emitted from Na systems
about 10% of events removed

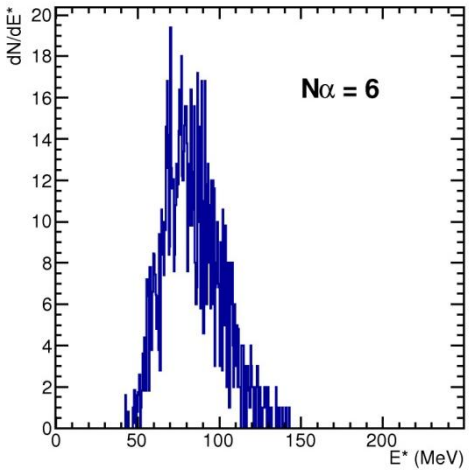
PF: 2 fragments (frag. and Na system)

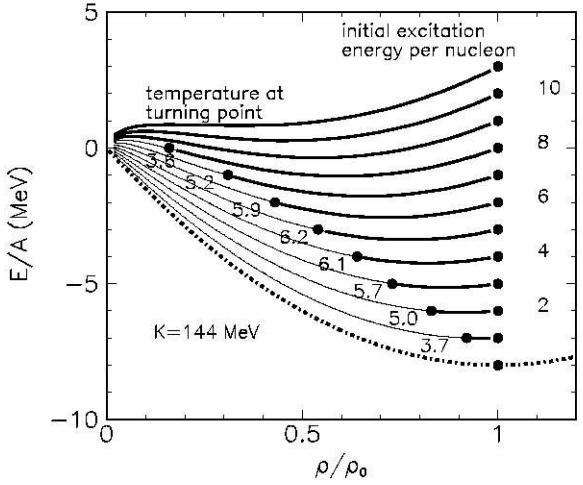
or

Projectile deexcitation (residue and evaporated α-particles) ?

Nα systems – E* distribution and minimal average density







Evolution of an isentropically expanding Fermi gas

<E*/A> : 3.3 -> 3.5 MeV

Low density EoS of finite nuclear systems:

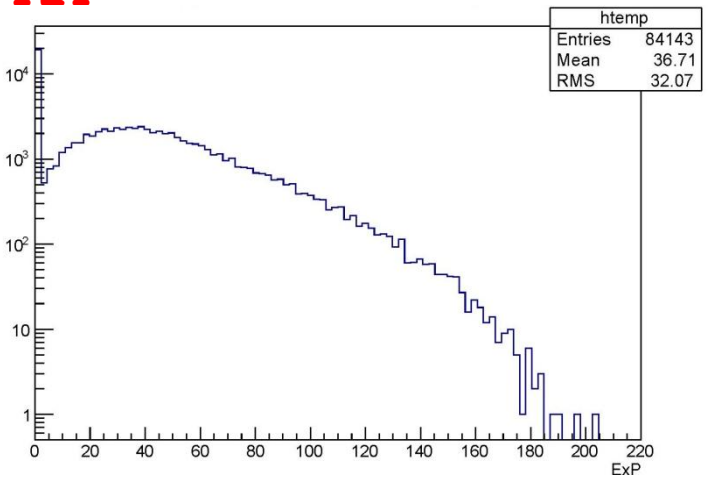
$(E/A)_{T=0} = 8\,[(\,1-\rho/\rho_0\,)^2 - 1]$

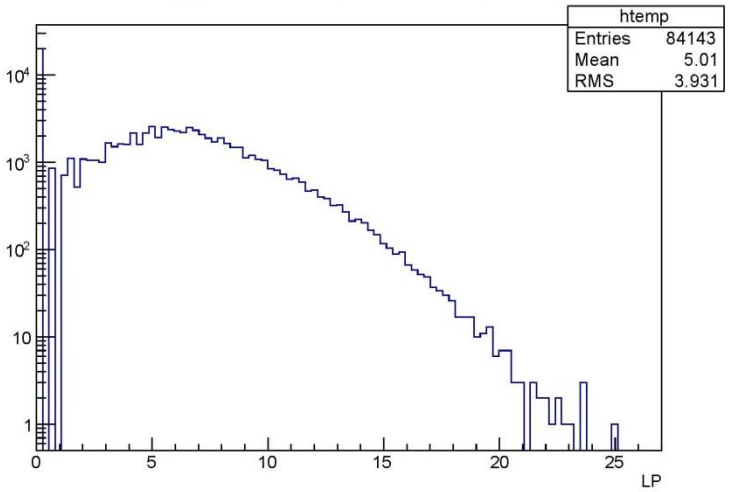
(W. Friedman PRC 42 (1990) 667)

Minimal average density estimate
≈ $0.7\rho_0$

Information on reaction mechanisms involved for the reaction used

- grazing angular momentum $l_{max}=90\hbar$, $l_{fus}=35\hbar$ (total fusion) and $l_{cf}=24\hbar$ (complete fusion) – P. Eudes et al. PRC 90 (2014) 034609
- for PF events ($Z_{PF}=20$) major features are reproduced by a model of stochastic transfers – L. Tassan-Got et al. NPA 524 (1991) 121





E* distrib.(MeV) and angular mom.distrib (ħ) for PF events

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Are α-particles emitted sequentially from excited projectiles ?

Are α-particles emitted sequentially or simultaneously from Na systems ?

Comparison to simulations with exp.velocity dist., exp. E* dist., ang.moment. dist.

Results of simulations

filtered by the multidetector replica including detection and identification details

Sequential emission: GEMINI++ code

Hauser-Feschbach formalism for evap. of particles (Z<5)

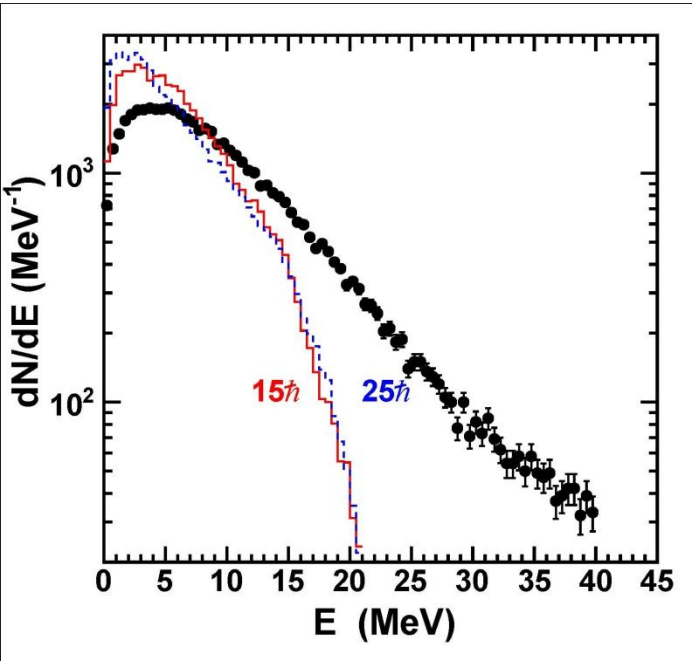
n, p, t, ^{3}He, α-particle, ^{6}He, $^{6-8}$Li and $^{7-10}$Be

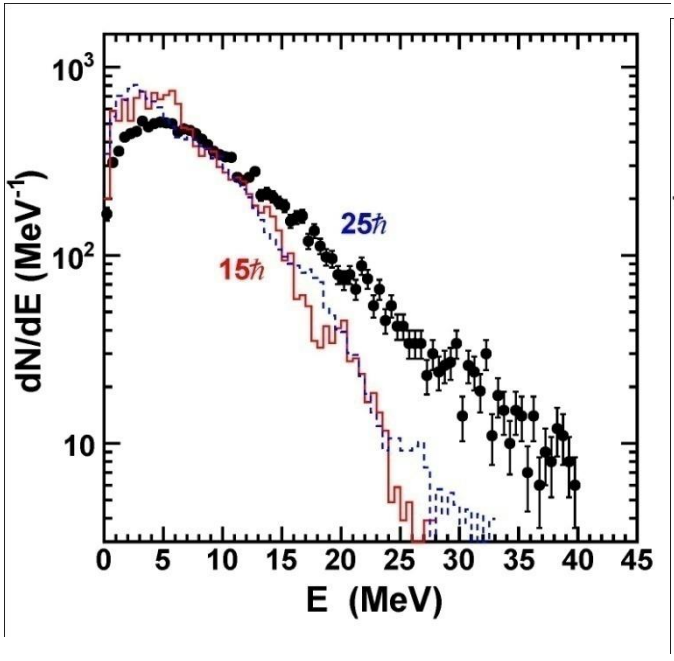
Transition state formalism for fragments (Z>4)

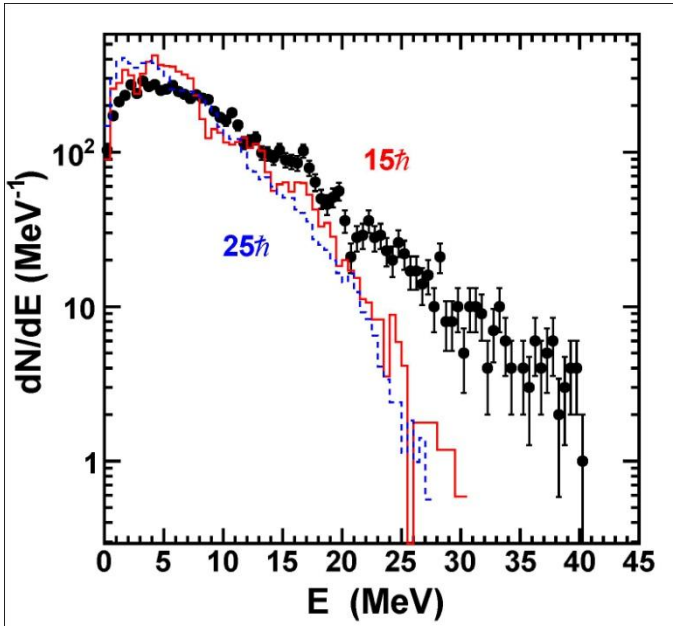
Hypothesis: the associated fragment is the evaporation residue of excited Ca projectiles ($E^* = E^*(Na) + E_{rel} + Q$)

GEMINI (histograms): reconstructed exp. E^* as input

$^{24}Mg + 4\alpha$ $^{20}Ne + 5\alpha$ $^{16}O + 6\alpha$







E_α in the Na c.m.

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Are α-particles emitted sequentially or simultaneously from Nα systems/sources ?

Simultaneous emission mimics a situation in which α clusters are early formed when the Nα system is expanding (theoretical predictions) due to thermal pressure.

i) Nα system splitted into N α in a freeze-out volume V_{fo} estimated by $V_{fo} = (\rho_0/\rho)V_0$

ii) an average Coulomb energy V_C at freeze-out is calculated by randomly localizing α-particles in V_{fo}

iii) the remaining available energy (E^*+Q-V_C) is randomly shared among the N α-particles such as to conserve energy and linear momentum

J.A. Lopez and J. Randrup, NPA 491 (1989) 477

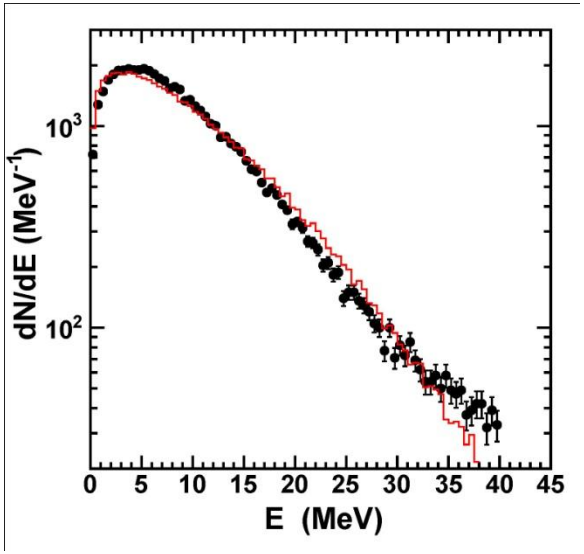
iiii) particles are propagated in the Coulomb field

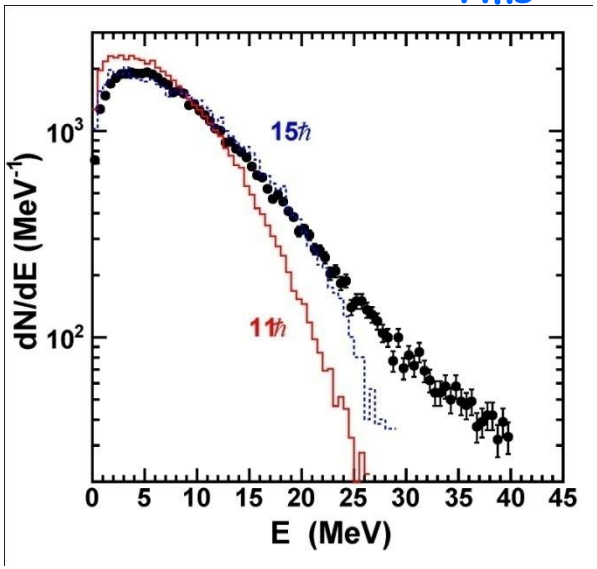
Nα systems ($^{16}O^*$, $^{20}Ne^*$, $^{24}Mg^*$) - energy spectra

Simultaneous emission

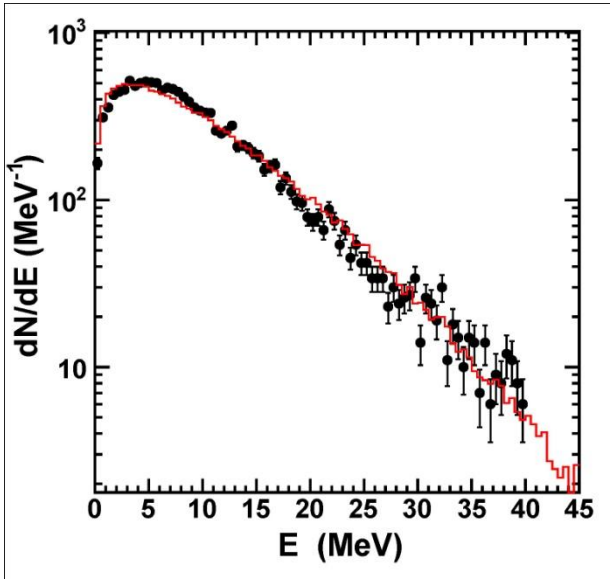
GEMINI (l_{rms}=1.5ħ)

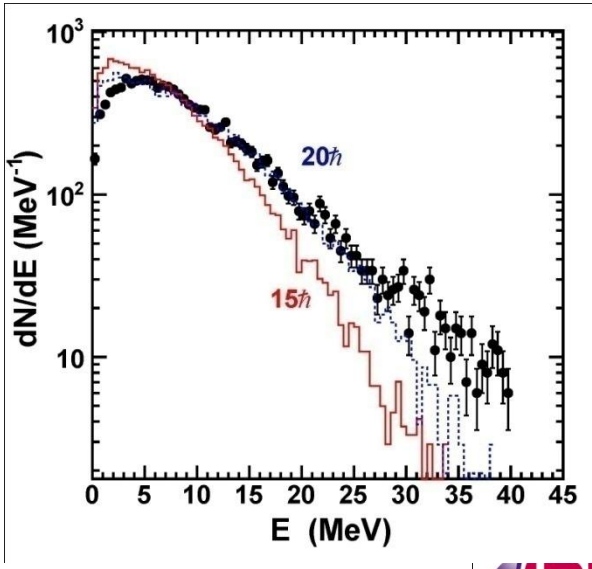
Nα=4





Nα=5





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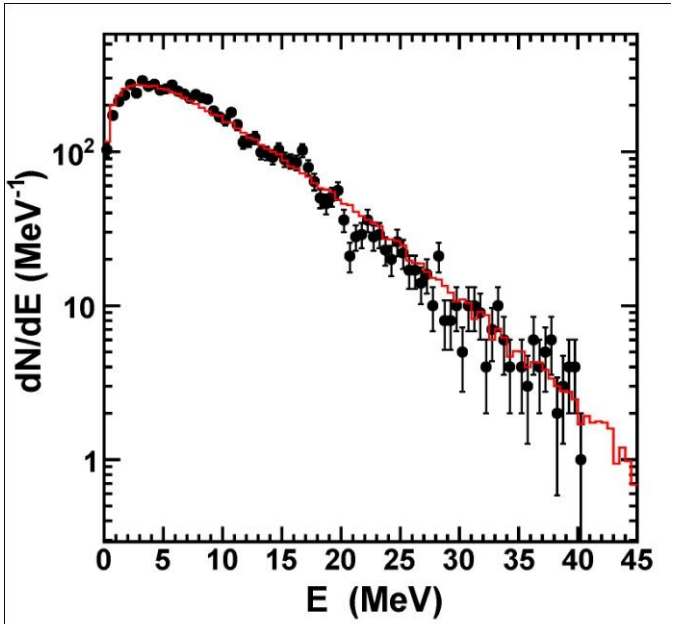
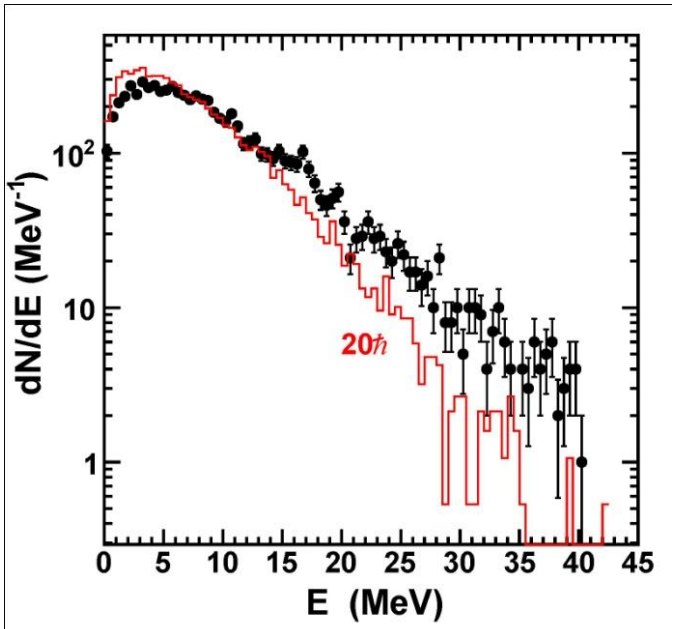
Nα systems ($^{16}O^*$, $^{20}Ne^*$, $^{24}Mg^*$) - energy spectra

Simultaneous emission

GEMINI

Nα=6





GEMINI results: large % for ^{8}Be evaporation along the chain and at the last evaporation step of the chain leaving an unstable ^{8}Be residue. Exp. Results from CF

M_{alpha}	1 ^{8}Be (%)		2 ^{8}Be (%)	
4	6.0 (0.2)	100.0	0.2 (0.05)	0.0
5	10.7 (0.6)	59.4	0.2 (0.1)	40.6
6	9.2 (0.8)	13.5	0.4 (0.2)	86.5

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Conclusions

The reaction $^{40}Ca+^{12}C$ at 25 MeV/nucleon was used to produce and carefully select minor classes of events from which excited Na sources can be unambiguously identified.

Their E* distributions are derived with mean values around 3.5 MeV per nucleon, which indicates that mean densities around about 0.7 the normal density have been reached.

Their energetic emission properties have been compared with two simulations

sequential decay (GEMINI++): energy spectra => rather poor agreement with data
^{8}Be production => total disagreement

simultaneous decay from expanding alpha-conjugate nuclei:
energy spectra => good agreement with data
^{8}Be production => out of the scope of the simulation

Evidence in favour of simultaneous emission (alpha-particle clustering) from expanding alpha-conjugate nuclei

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