The experimental study I am presenting today was inspired by discussions I had with Peter about ten years ago

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Temperature and density conditions for alpha clustering in alpha-conjugate nuclei

$^{40}Ca+^{12}C$, 25 AMeV
with CHIMERA multidetector (LNS Catania)

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Outline of the talk

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

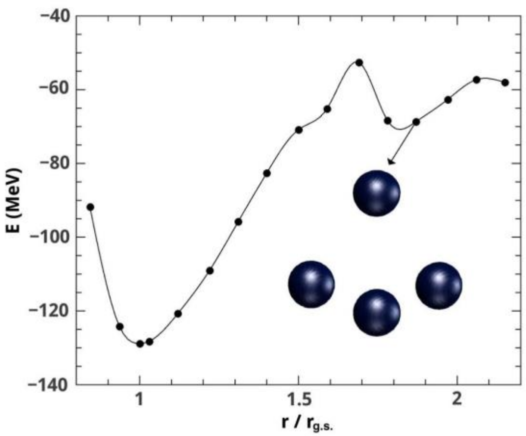
Experimental strategy and experiment - How to isolate alpha-conjugate sources with selections

Results i) comparisons to simulations (seq. versus simul. emission) to sign a clustering

ii) extract T and density conditions

Conclusion

Constrained Hartree-Fock-Bogoliubov approach using Gogny D1S int. ^{16}O, ^{20}Ne …
Constrained self-consistent relativistic Hartree-Bogoliubov (RHB) model based on DD-ME2 effective interaction both by imposing radial deformation



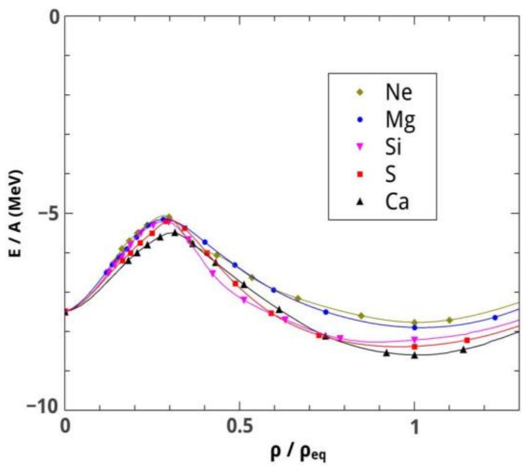


FIG. 5 (color online). Equation of state for a choice of self-conjugate nuclei (EOS-A) as a function of average density scaled by the one at equilibrium; see text for detailed definition.

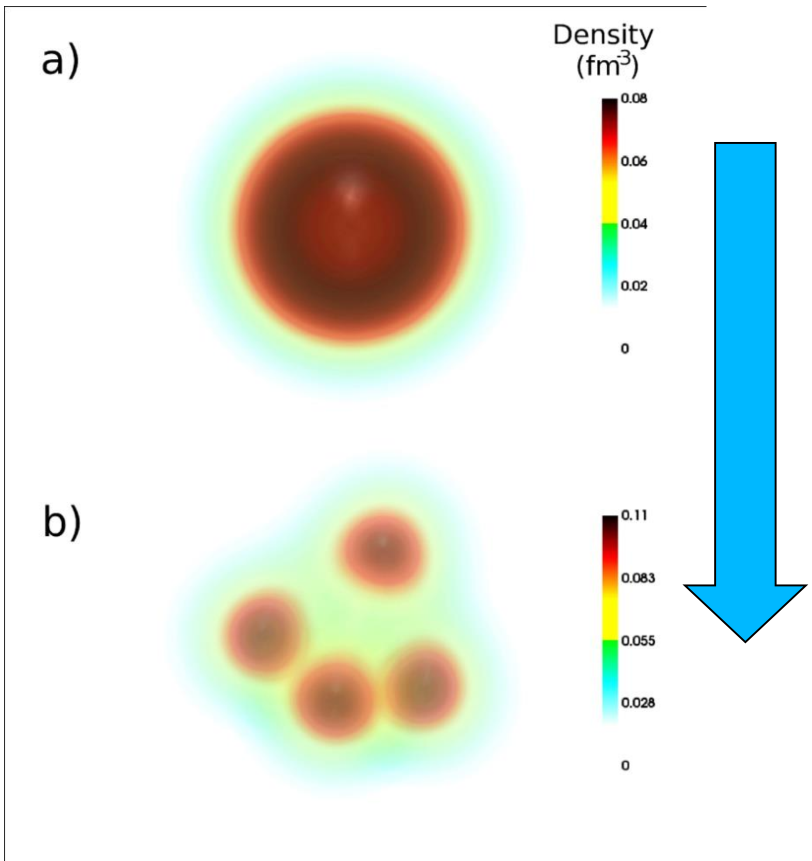


FIG. 3: (Color online) Self-consistent intrinsic nucleon density of ^{16}O for a radius constrained to 3.32 fm (a) and 3.34 fm (b).

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

more pronounced cluster structure compared to non-relativistic functionals

M. Girod and P. Schuck, PRL 111 (2013) 132503 J.-P. Ebran, E. Khan 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

1192 telescopes 94% of 4π

Si ≈ 200-300 μm

CsI(Tl) from 12 to 3 cm

beam intensity: 10^7 ions/s

thin target 320μg/cm^2

to avoid random coinc.

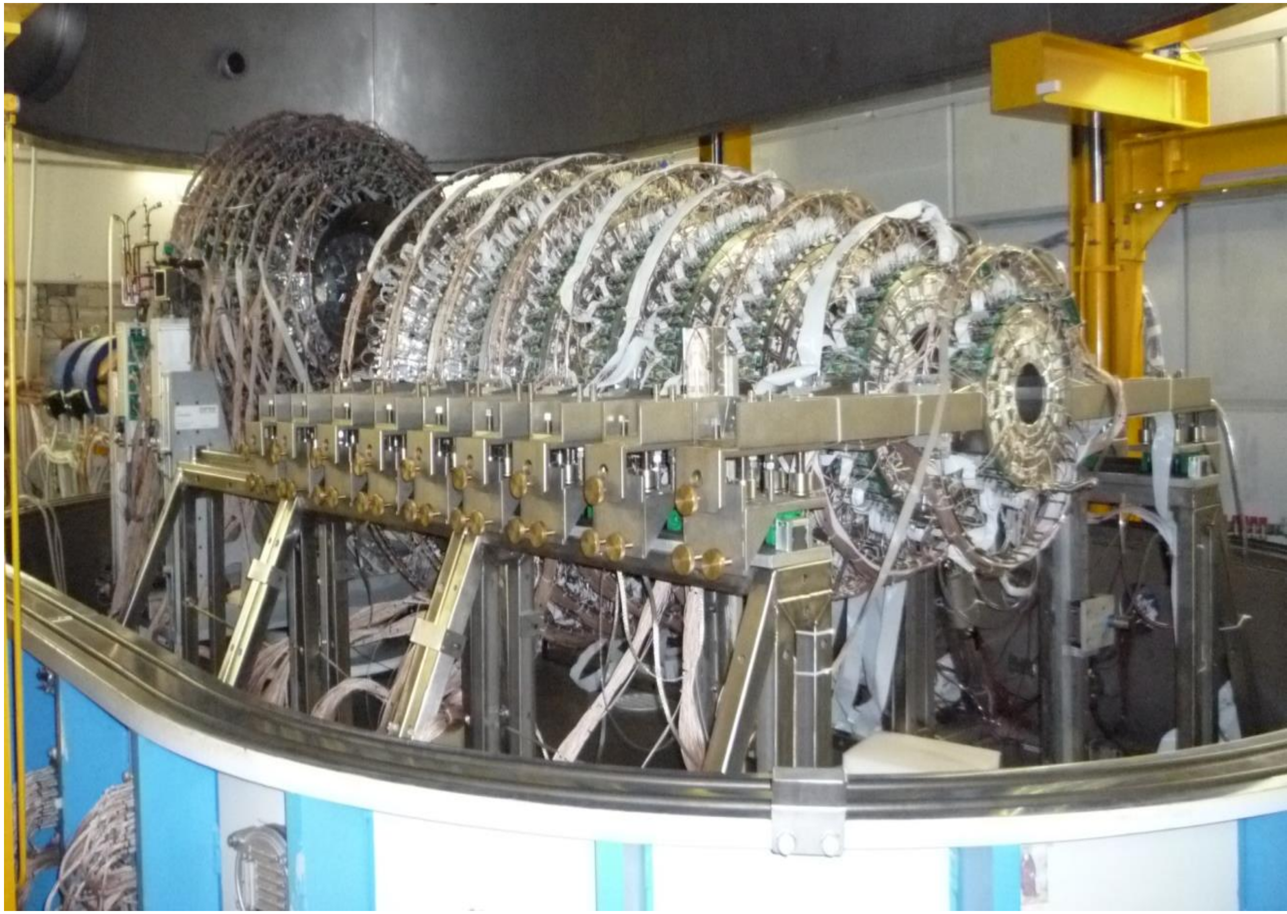
angular range used: Θ=1-62°

=> 816 telescopes

Identification in Z and A

for the energy range and

reaction products of interest



alpha-particles of interest loose the major part of their energy in CsI(Tl):

dedicated energy calib. from time of flight – energy resolution 1-2.5%

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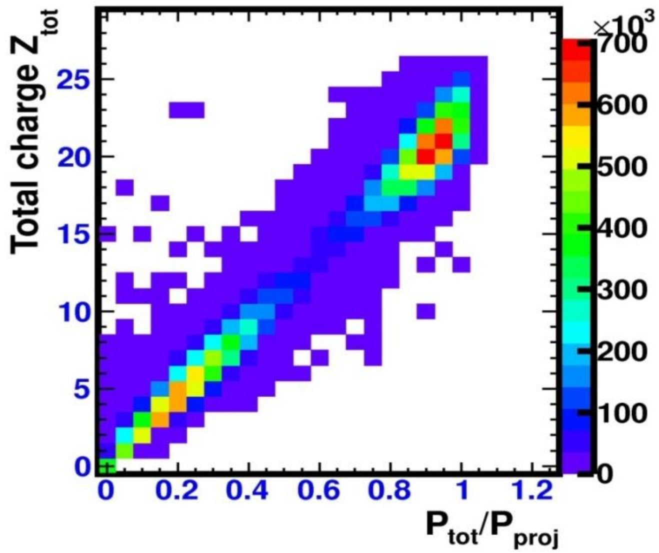
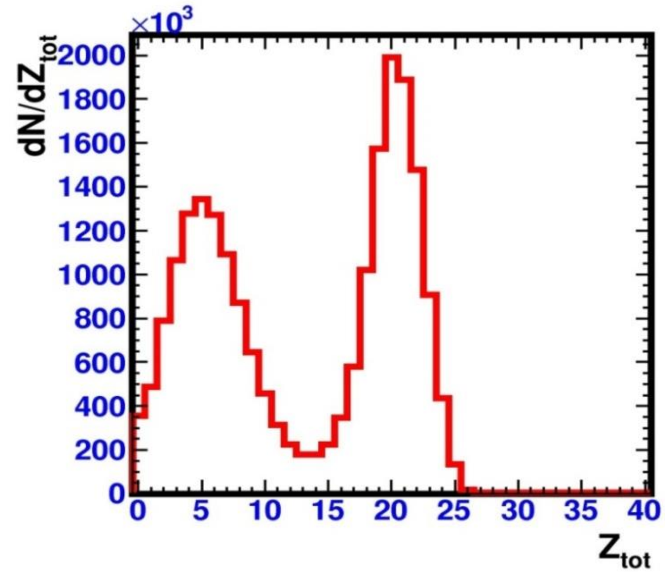
Overview of event reconstruction/identification

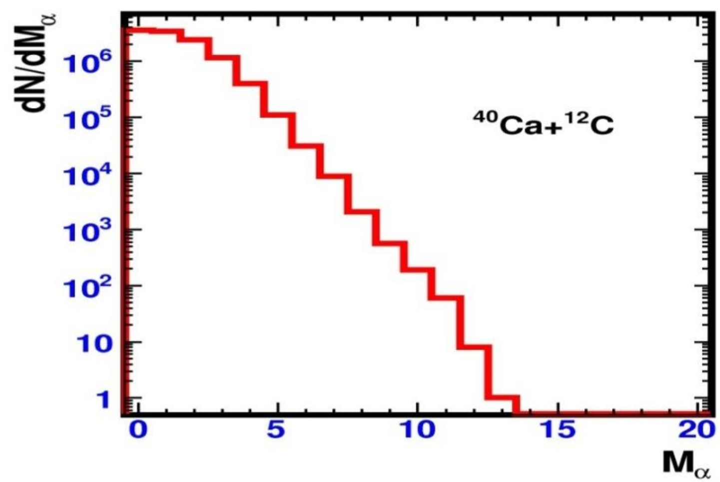
grazing angle = 1.11°- ring 1I (1.0°-1.8°) suppressed to eliminate elas./ quasi elas.





from geometrical efficiency
well measured events

=> $Z_{tot} \geq 19$

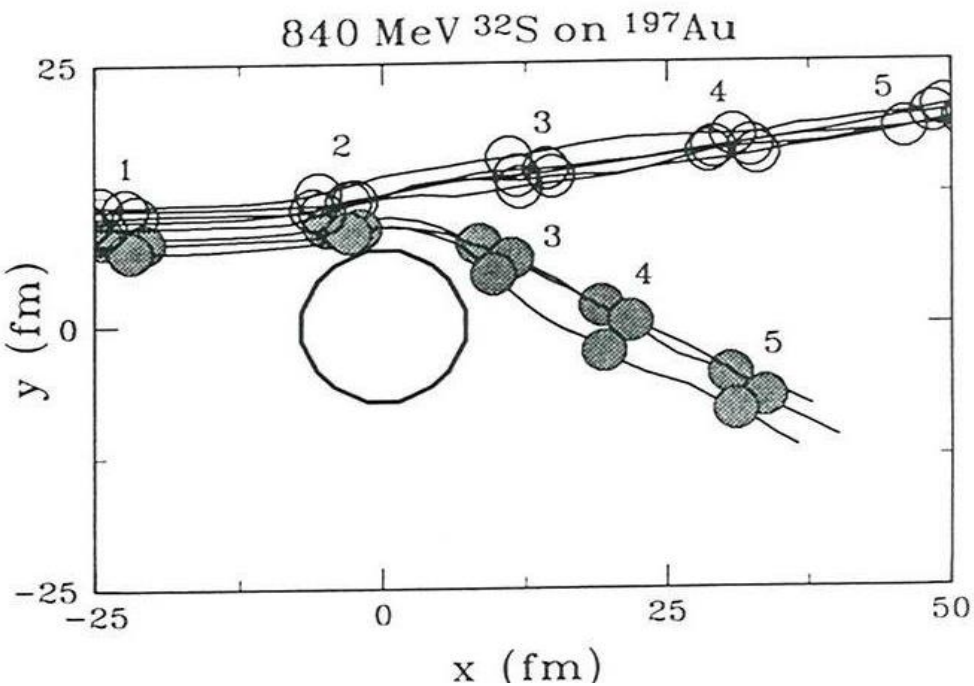


Selected mechanism: Proj. Frag. (PF) => $Z_{tot}=20$

Selected events?

^{32}S ≈ 26 AMeV - surface friction model + alpha substructure of the projectile + random force (elastic α – α scattering cross section)

H. Fuchs and K. Mohring, Rep. on Prog. in Physics 57 (1994) n°3



^{20}Ne
(weakly excited)
quasi elastic traj.

$^{12}C^*$
much more excited
significantly slowed down
deflec. to negative angles

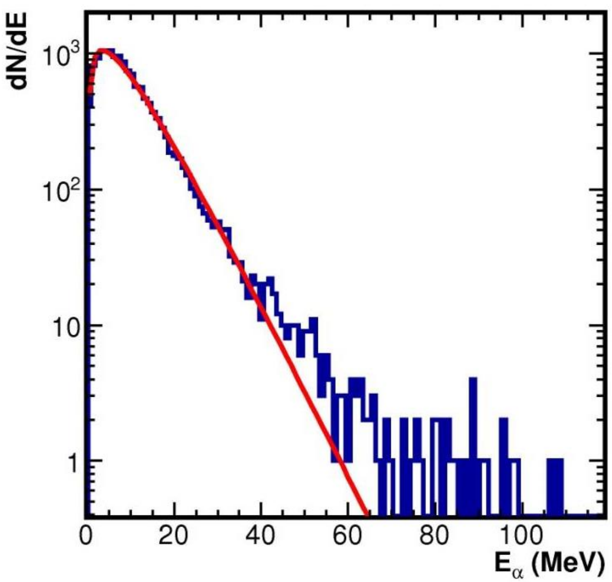
For ^{40}Ca=>1 excit. PF which deexcites into alphas (M_α=4,5,6,7) + a single weakly excited frag.($Z_{frag}=20-2xM_\alpha$)

Selected mechanism - Proj. Frag. (PF) $Z_{tot}=20$
Selected events: ($M_{alpha}=4,5,6,7$) + one frag.($Z_{frag}=20-2xM_{alpha}$)

Alpha energy spectrum in the Na c.m. $M_{alpha}=5$

Maxwellian distribution

Presence of preequil.



The question is: does M_{alpha} come exclusively from a single set of excited α-conjugate nuclei? called also Na sources in what follows

Additional selections

Some α-particles from preequil.

Some α-particles from $^{12}C^*$, $^{16}O^*$ (unbound states) either fragments or emitted from Na systems

=> about 10% of events removed

see B.B. et al., PLB 755 (2016) 475,
J. Phys. Conf. Ser. 863 (2017) 012054

⇒ After selections the answer is yes

Different M_{alpha} come exclusively from sets of excited α-conjugate nuclei

Next step: deexcitation mode ?

<E*> ? T? density ?

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Deexcitation mode

Are a-particles emitted sequentially or simultaneously from Na sources ?

Answer by comparing to simulations

Simulations with exp.velocity dist., exp. E* dist., and ang.moment. dist. as inputs

Results of simulations

filtered by the multidetector replica including detection and identification details – detection efficiency (46.7 to 27.2% when Ma varies from 4 to 7)

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

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)

Best agreement with data is obtained with gaussian distributions (RMS=1.5ħ) for spin inputs

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

i) Nα systems split into N α

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

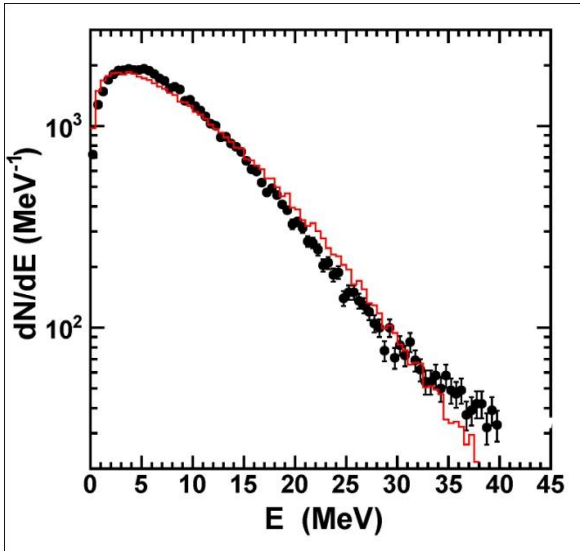
J.A. Lopez and J. Randrup, NPA 491 (1989) 477

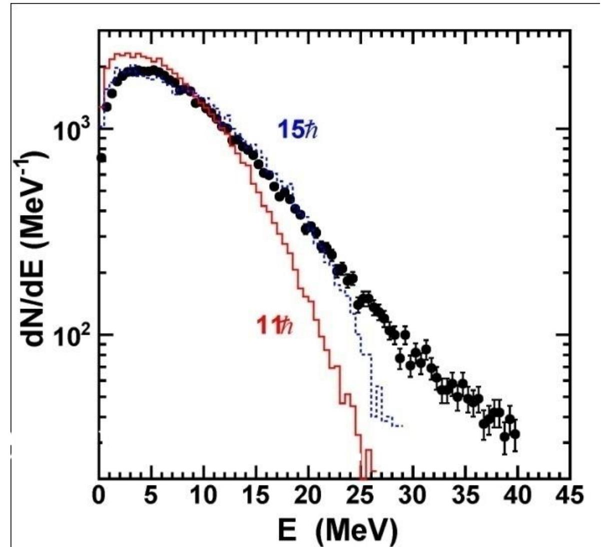
Similar calculated energy spectra are obtained with simulations containing an intermediate freeze-out volume step where α are formed and then propagated in their mutual Coulomb field => density information

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

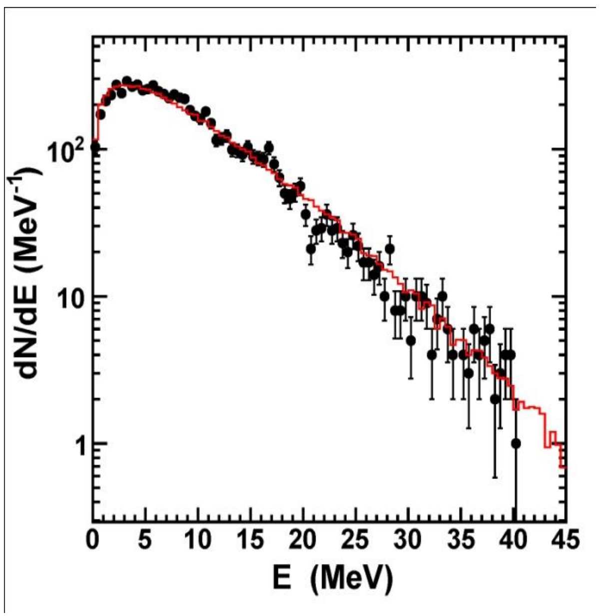
Simultaneous emission | GEMINI

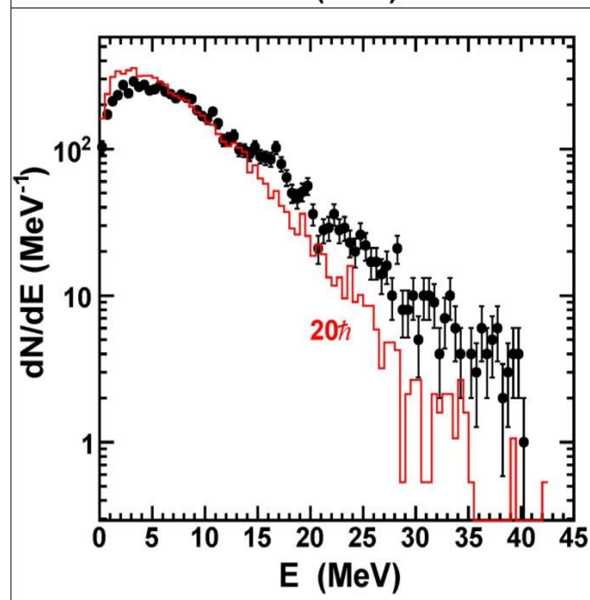
Nα=4
$^{16}O^* \to 4\alpha$





Nα=6
$^{24}Mg^* \to 6\alpha$





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T and density from energy spectra

Information deduced from Maxwellian fit with volume/breakup pre-exponential factor

A. Goldhaber, PRC 17,2243 (1978)

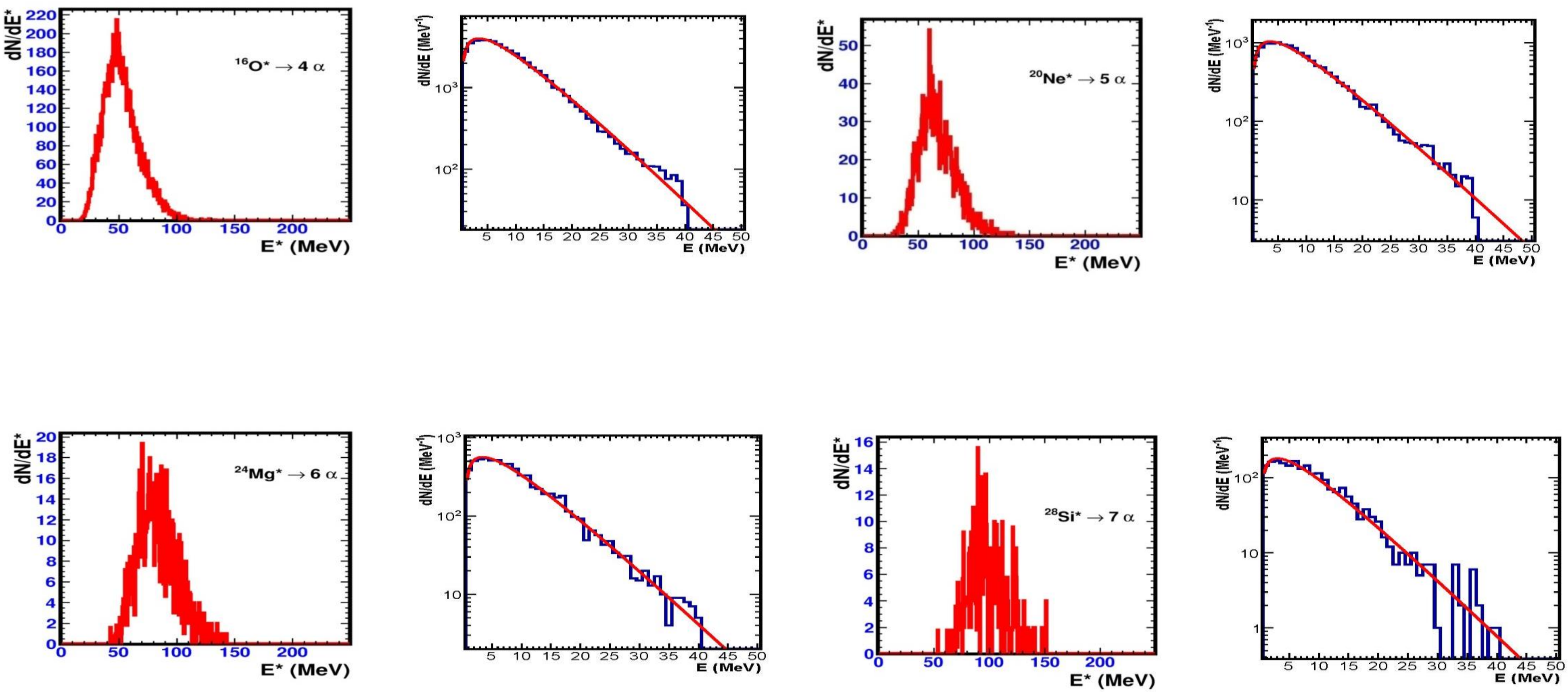
=> $dN/dE = N_0 \, (E - C_C)^{1/2} \exp[-(E - C_C)/T]$

Coulomb correction C_C

Most probable value of $dN/dE = T/2 + C_C$

Comparison with simultaneous simulation with Freeze-Out step to derive F.O. volume values and consequently density

Excitation energy and Energy spectra



B.B. et al., Symmetry 13, 1562 (2021)

T and density from energy spectra

Nα	⟨E*⟩ (MeV)	T (MeV)	Cc (MeV)	ρ/ρo
16O*	52.4	6.15 (0.03)	0.33 (0.03)	0.37 (0.04)
20Ne*	67.3	6.22 (0.05)	0.45 (0.05)	0.36 (0.04)
24Mg*	83.5	5.92 (0.07)	0.40 (0.07)	0.34 (0.06)
28Si*	98.5	5.40 (0.12)	0.37 (0.16)	0.34 (0.11)

=> ⟨E*⟩≈ 3.3-3.5 AMeV   T≈ 5.5-6.0 MeV   density ≈ 1/3 ρo

B.B. et al. Symmetry 13, 1562 (2021)

Conclusion

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

When compared with simulations (sequential decay and simultaneous decay) evidence in favour of simultaneous emission (alpha-particle clustering) from expanding alpha-conjugate nuclei is deduced

Their E* distributions are derived with mean values around 3.5 MeV per nucleon.

T around 5.5-6.0MeV and density around 1/3 saturation density were extracted from energy spectra. Density is in qualitative agreement with self-consistent mean field calculations at zero temperatures.

Finite temperature calculations would be welcome for a more valid comparison with the data

N_{alpha} sources - excitation energy versus temperature from surface/sequential emission

$$dN/dE = N_0 (E-B_C)/T \exp[-(E-B_C)/T]$$

Na	T (MeV)	Bc (MeV)
4	5.18 (0.03)	-1.19 (0.06)
5	5.14 (0.05)	-0.92 (0.11)
6	4.94 (0.07)	-1.05 (0.16)
7	4.57 (0.11)	-1.12 (0.30)

B_C is negative => no physical meaning

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Multi-particle correlation function

R. Charity et al., PRC 52 (1995) 3126

to identify and select nuclei/excited states

N alphas => determination of the alpha emitter reference frame => $E_{tot}=\sum E_k^i$

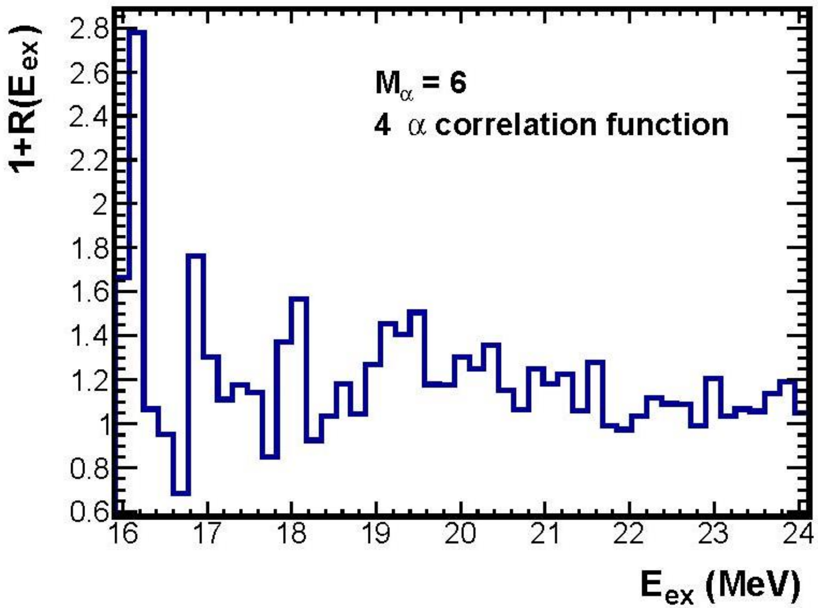
Correlation function:

$$1+R(E_{tot})=Ycorr(E_{tot})/Yuncorr(E_{tot})$$

$Yuncorr(E_{tot})$: product of single particle yields or mixing particles from different events

M. A. Lisa et al., PRC 44 (1991) 2865

% of events removed containing $^{12}C^*$, $^{16}O^*$ and $^{20}Ne^*$ fragments which deexcite into α-particles or Na sources which deexcite via $^{12}C^*$, $^{16}O^*$ and $^{20}Ne^*$



Statistically significant peaks are located in the E_{ex} range 16.7-22.0 MeV

16.84 + 17.20, 17.72 + 18.09, 19.26 + 19.54, 20.05 + 20.41, 21.05 and 21.65 MeV (0+ to 6+)
Known as 100% alpha emitters

multi-particle CF: for events « participating » to an unbound state a percentage is kept (from 1 to 95%) which corresponds to CF background under the peak 1-[(CF-1)/CF] = (1/CF)

M_{alpha}	% supp. evts	final N of selected evts
4	1.6 (0.1)	12780
5	3.1 (0.3)	2623
6	3.6 (0.5)	1129
7	3.9 (1.1)	291

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Constrained Hartree-Fock-Bogoliubov approach
^{16}O, ^{20}Ne ...

When A increases no more potential well at low density

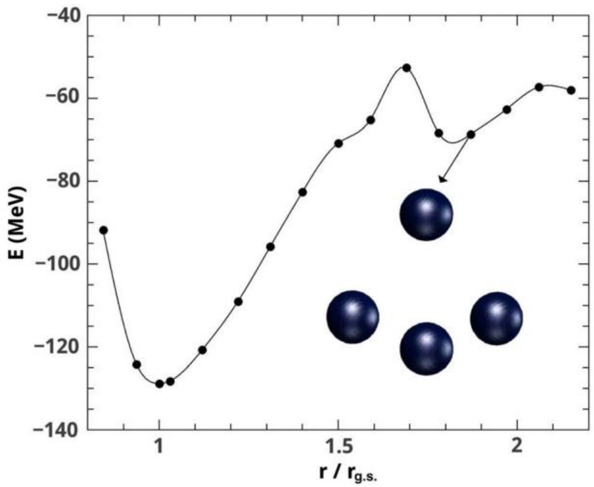


FIG. 1 (color online). Total energy of ^{16}O as a function of the radius scaled with respect to the one of the ground state $r_{g.s.}$. At $r/r_{g.s.} = \sim 1.8$, we see that a tetrahedron of four α particles is formed. No c.m. correction for individual α's is applied here. The arrow indicates to which $r/r_{g.s.}$ value the α configuration corresponds.

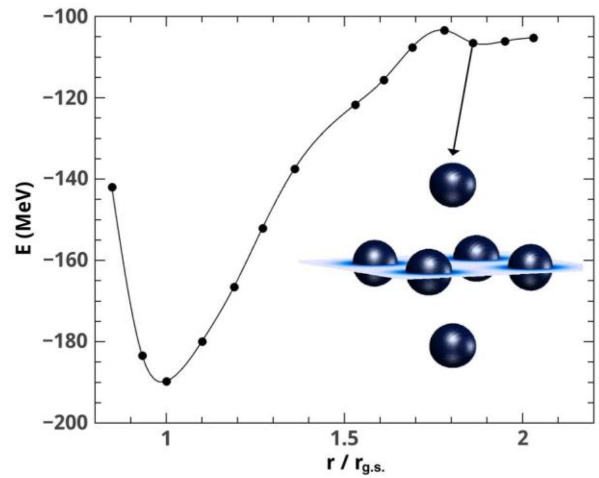


FIG. 2 (color online). Same as Fig. 1 but for ^{24}Mg with six α's. The shaded area only serves to show the three dimensionality of the α arrangement.

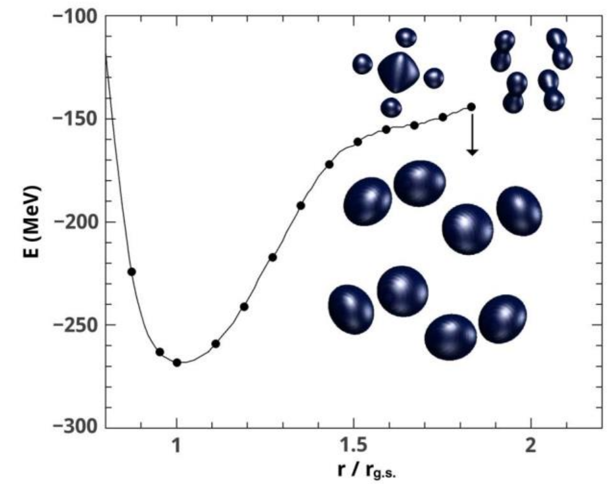


FIG. 3 (color online). Same as Fig. 1 but for ^{32}S with eight α's. Also, configurations with four ^{8}Be and a ^{16}O surrounded by four α's are shown.

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

Quality of energy calibration ?

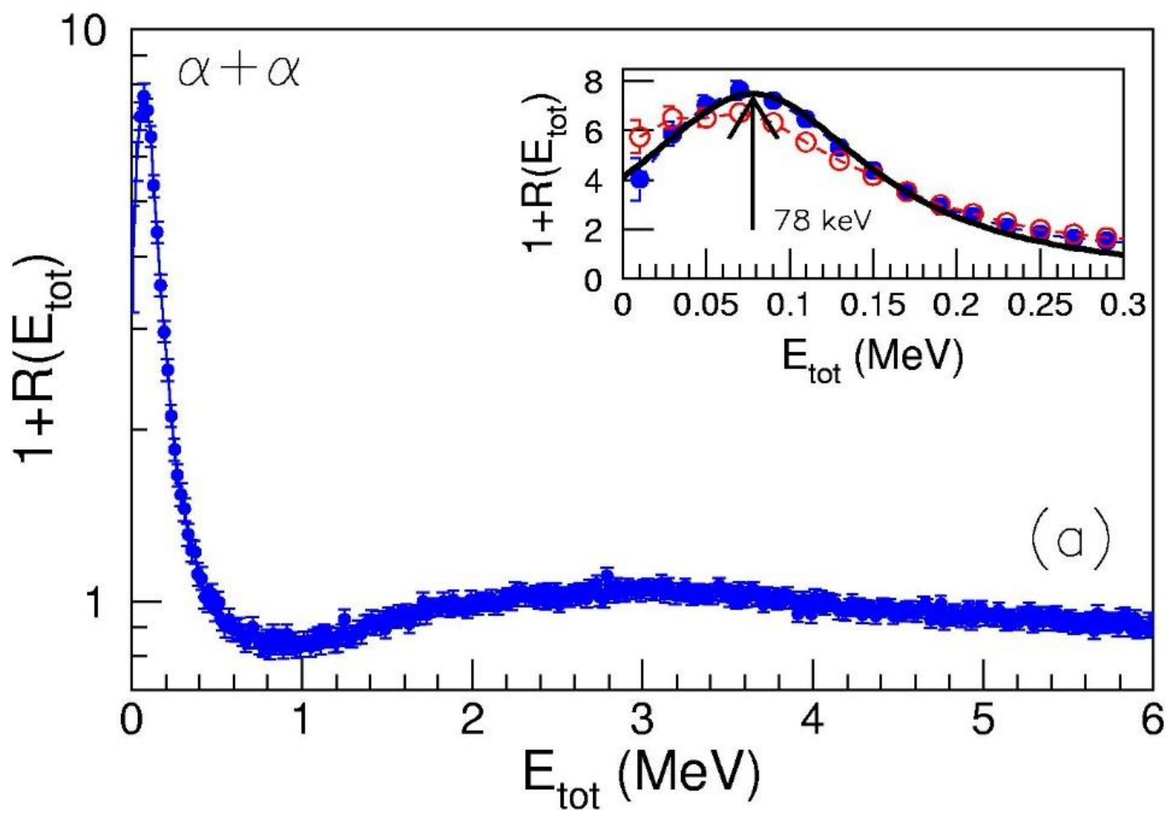
Two-alpha correlation function

^{8}Be

E_{tot}=92 keV (Γ=5.6 eV)

Exp: 78 keV

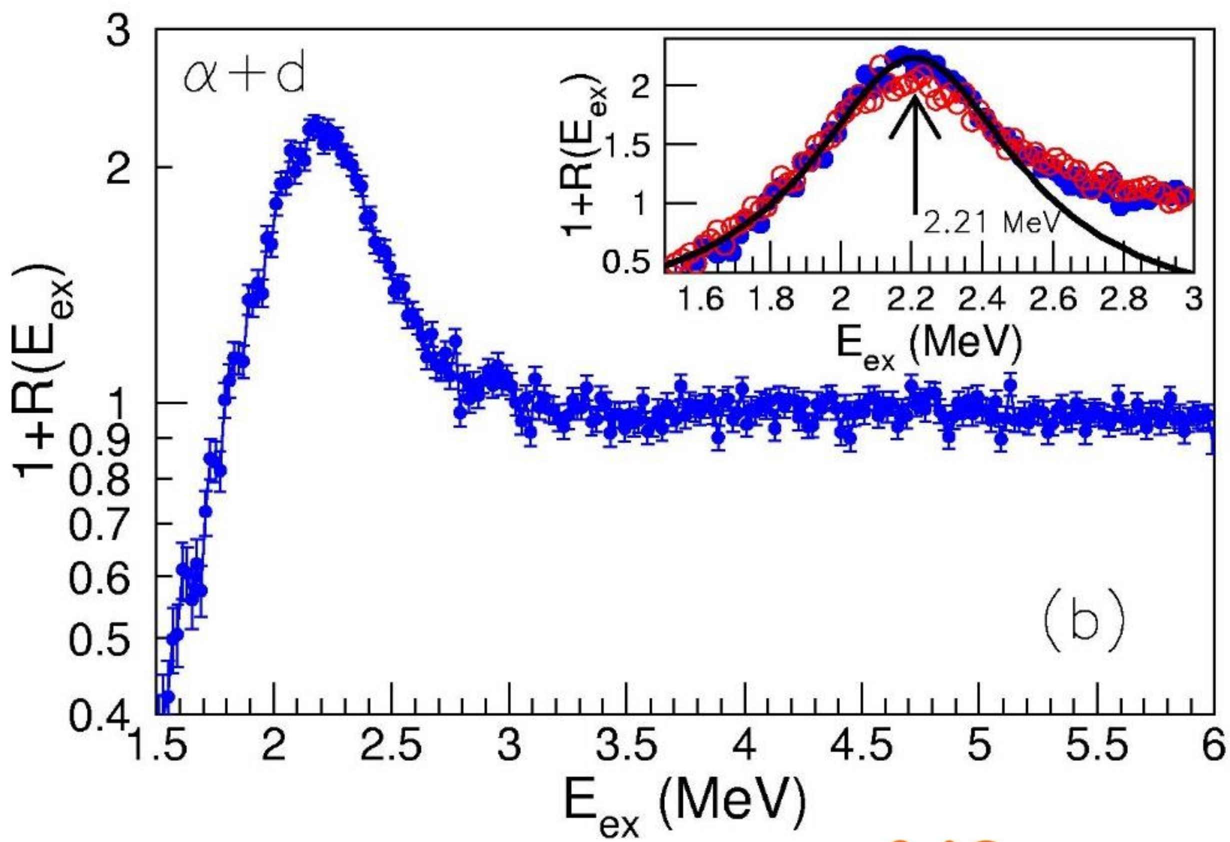
Angle under which particle is emitted (finite granularity)
Dir. of velocity vector:
geometrical center of the module
random angle in the geometrical extension of the module



Quality of energy calibration ?
d-alpha correlations

$^6Li^*$
$E_{ex}=E_{tot}-Q$
E_{ex}= 2.186 MeV

Exp: 2.21 MeV



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