Temperature and density of hot decaying ^{40}Ca and ^{28}Si

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During the last decade it was theoretically shown that dilute symmetric nuclear matter may experience Bose particle condensation. This possible new phase of nuclear matter may have its analog in low-density states of α-conjugate lighter nuclei.

Theoretical calculations show that self-conjugate N = Z nuclei will cluster into a metastable phase of α particles at excitations above 3MeV/nucleon and densities below 0.33 normal density

The preliminary results of temperature and density of hot decaying ^{40}Ca and ^{28}Si will be presented. The method used allows to trace important quantum effects such as fermion quenching or Bose - Einstein Condensation in nuclei.

Event selection - what we need

- careful isolation of the equilibrated source
- elimination of particles emitted before equilibrium
- events with fragments that have an α-like (i.e. ^{12}C, ^{16}O, etc.) or d-like structure (^{6}Li, ^{10}B, etc.).

Event selection - what we have

Investigation of ^{40}Ca + ^{40}Ca at 35 MeV/A:

- subject: peripheral and midperipheral collisions leading to excited projectile-like fragments
- total equilibration of all degrees of freedom is not achieved in the midperipheral collisions
- Z = 1 particles and neutrons are primarily pre-equilibrium particles, representing energy dissipation but not energy deposition into the PLF
- a hierarchy effect is observed in the collision dynamics
- mechanism significantly increases the difficulty of isolating clean projectile decay samples

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Event selection

1. $A_{TOT} = 40 + A_{LCP}$:
   - even - even fragments
   - odd - odd fragments
   - even - odd fragments
   - mixed fragments
   - bosonic fragments
   - fermionic fragments
2. α-like mass = 40 and α-like fragments
3. α-like mass = 40 and 10 α
4. d-like mass = 40 and d-like fragments

Excitation energy calculations

Total excitation energy:

$$E^*_{TOT} = \sum_i K^i - Q$$

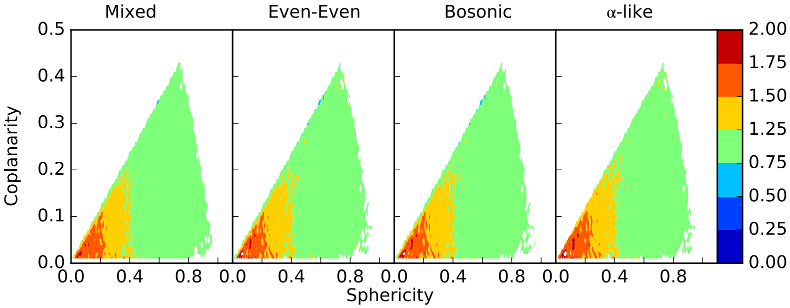
Transverse excitation energy (to minimise contributions from entrance-channel effects, predominant in the beam direction):

$$E^*_{TH} = \frac{3}{2} \sum_i K^i_{\perp} - Q$$

For a completely equilibrated system, the transverse kinetic energy (times 3/2) is equal to the total kinetic energy.

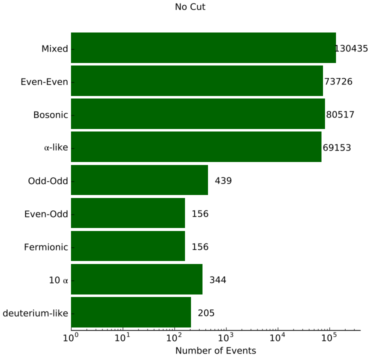
equilibrium observable: $E^*_R = \frac{E^*_{TOT}}{E^*_{TH}}$

E_R^* on Z-axis



$0.8 < E_R^* < 1.2$

Event selection - statistics



THE METHOD - CLASSICAL AND QUANTUM CASE

classical case:

$$\sigma^2_{xy} = \bar{N} 4 m^2 T^2$$

quantum case:

$$\sigma^2_{xy} = \bar{N} 4 m^2 T^2 QF$$

QF - quantum factor, different for bosons and fermions

For bosons, the below and above T_0 case has to be considered. In this presentation - the below T_0 case will be shown.

Physics Letters B 696 (2011) 178–181
Nuclear Physics A 892 (2012) 43–57
Nuclear Science and Techniques 24 (2013) 050512
Phys Rev C 86 (2012) 027602

The method - Coulomb corrections

$$\langle Q_{xy}^2 \rangle = (2mT)^2 \frac{4}{15} \frac{\int_0^\infty dy y^{\frac{5}{2}} \frac{1}{e^{y+\frac{A'}{yVT^2}-\nu}\pm 1}}{\int_0^\infty dy y^{\frac{1}{2}} \frac{1}{e^{y+\frac{A'}{yVT^2}-\nu}\pm 1}}$$

$$\langle \frac{(\Delta N)^2}{\bar{N}} \rangle = \frac{\int_0^\infty dy y^{\frac{1}{2}} \frac{e^{y+\frac{A'}{yVT^2}-\nu}}{e^{y+\frac{A'}{yVT^2}-\nu}\pm 1}}{\int_0^\infty dy y^{\frac{1}{2}} \frac{1}{e^{y+\frac{A'}{yVT^2}-\nu}\pm 1}}$$

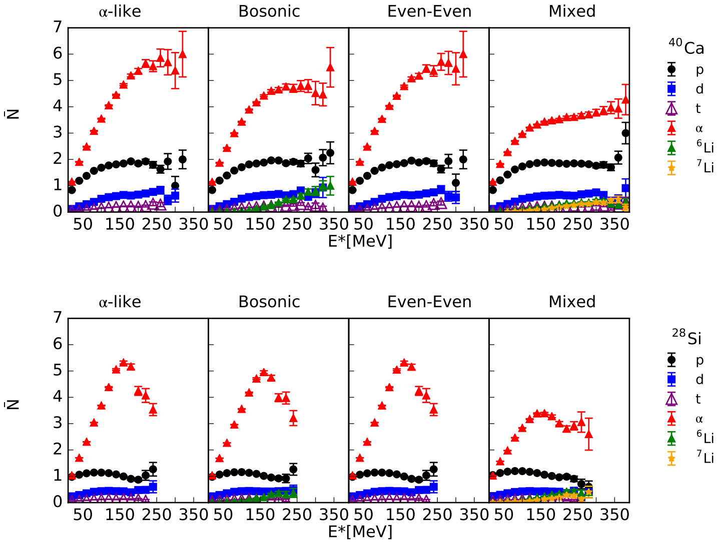
$$\bar{N} = \frac{gV}{h^3} 4\pi \frac{(2mT)^{3/2}}{2} \int_0^\infty dy y^{\frac{1}{2}} \frac{1}{e^{y+\frac{A'}{yVT^2}-\nu} \pm 1}$$

V, T, ν are the roots of the equations, $A' = 1.44 \frac{4\pi\hbar^2 Z_{particle} Z_{source}}{2m}$

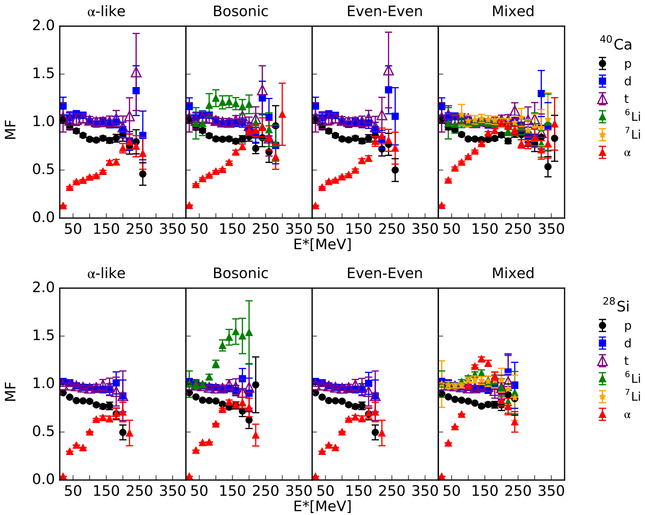
$$\rho = \frac{g}{h^3} 4\pi \frac{(2mT)^{3/2}}{2} \int_0^\infty dy y^{\frac{1}{2}} \frac{1}{e^{y+\frac{A'}{yVT^2}-\nu} \pm 1}$$

Phys Rev C 88 (2013) 024607, H. Zheng PhD thesis

Average Multiplicity $\bar{N}$



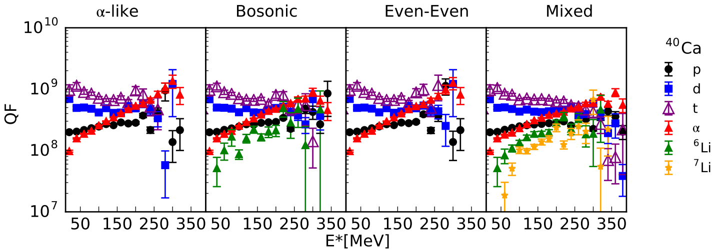
Multiplicity Fluctuations MF

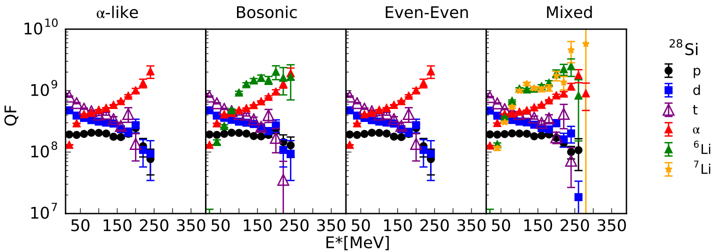


XG. Cao et al., Evidence for high excitation energy resonances in the 7 alpha disassembly of 28Si,

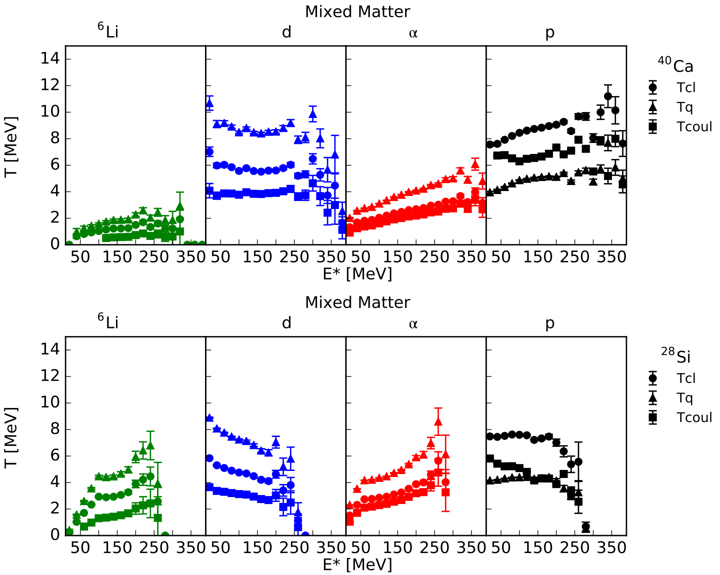
https://arxiv.org/abs/1801.07366

Quadrupole Fluctuations QF

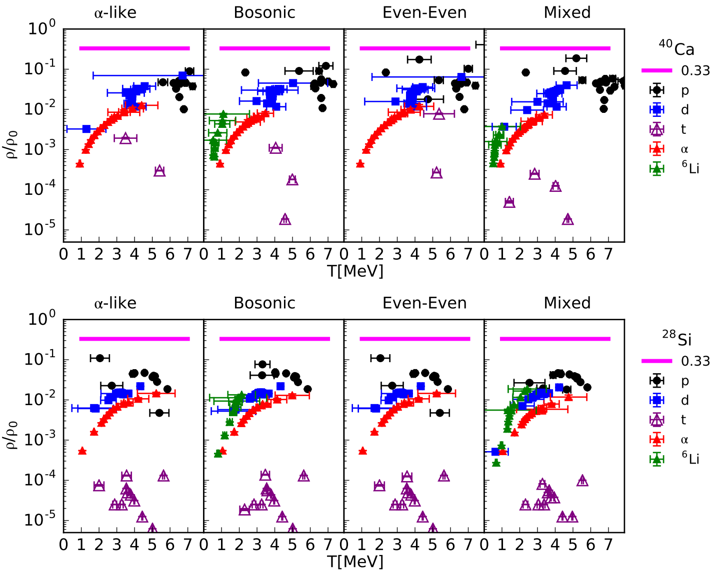




Temperature distribution

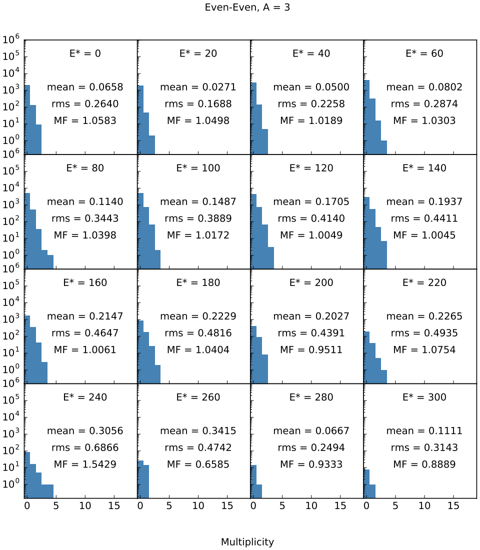


Density distribution



Summary

- density and temperature of hot decaying PLFs have been extracted
- we obtained similar results, regardless the event selection
- we observe different temperatures of the PLF at the emission of each particle and therefore different time scales of the different particle-types emission.
- bosons experience higher densities than tritons; protons seem to be emitted from the same region of the nuclei as bosons
- the comparison with the theoretical calculations will be performed
- the above T_0 case for bosons will be performed
- the calculations of T and ρ of decaying ^{28}Si for other type of matter is ongoing.
- the hypothesis the THSI are the BEC needs to be confirmed


Even-Even, A = 3
E* = 0
mean = 0.0658
rms = 0.2640
MF = 1.0583
E* = 20
mean = 0.0271
rms = 0.1688
MF = 1.0498
E* = 40
mean = 0.0500
rms = 0.2258
MF = 1.0189
E* = 60
mean = 0.0802
rms = 0.2874
MF = 1.0303
E* = 80
mean = 0.1140
rms = 0.3443
MF = 1.0398
E* = 100
mean = 0.1487
rms = 0.3889
MF = 1.0172
E* = 120
mean = 0.1705
rms = 0.4140
MF = 1.0049
E* = 140
mean = 0.1937
rms = 0.4411
MF = 1.0045
E* = 160
mean = 0.2147
rms = 0.4647
MF = 1.0061
E* = 180
mean = 0.2229
rms = 0.4816
MF = 1.0404
E* = 200
mean = 0.2027
rms = 0.4391
MF = 0.9511
E* = 220
mean = 0.2265
rms = 0.4935
MF = 1.0754
E* = 240
mean = 0.3056
rms = 0.6866
MF = 1.5429
E* = 260
mean = 0.3415
rms = 0.4742
MF = 0.6585
E* = 280
mean = 0.0667
rms = 0.2494
MF = 0.9333
E* = 300
mean = 0.1111
rms = 0.3143
MF = 0.8889
Multiplicity