Condensation Bose-Einstein en physique nucléaire

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

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(ISOSPIN COLLABORATION)

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Outline of the talk

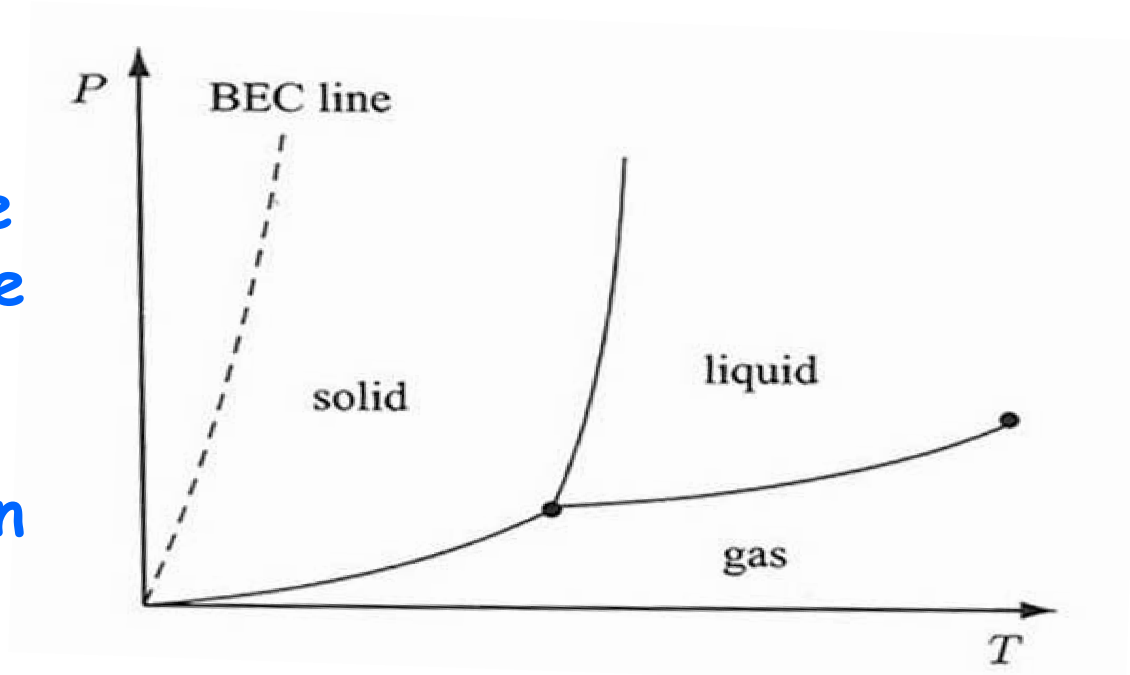
- Introduction on BEC and historical survey
- BEC in the nuclear physics context
- Experimental strategy and experiment
- Results
- Perspectives

The ideal Bose gas for valuable guidance and predictions

typical P-T phase diagram with the exception of He

P(T) line characterizing the BEC phase transition of the ideal Bose gas

Above this line BEC gas can only exist in conditions of metastability



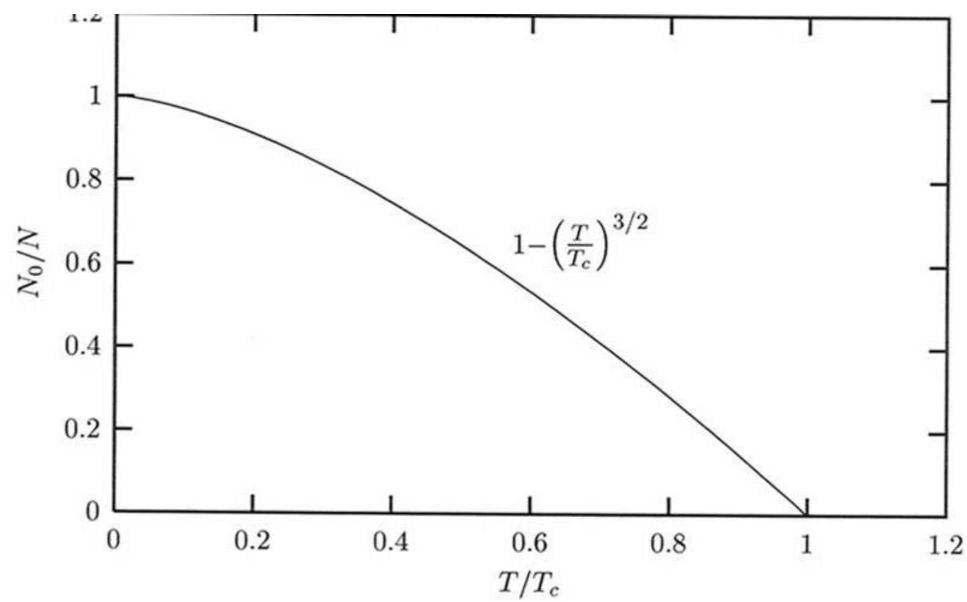
The ideal Bose gas for valuable guidance and predictions

Criteria for BEC

$k_B T_c = 2\pi\hbar^2/m\ (n/2.612)^{2/3}$
T_c fully determined by the density (n=N/V) and the mass of the constituents

$v_c = \lambda_T^{\,3}/2.612$
critical volume defined for a fixed value of T
BEC takes place if $v < v_c$

Ideal Bose gas in a box



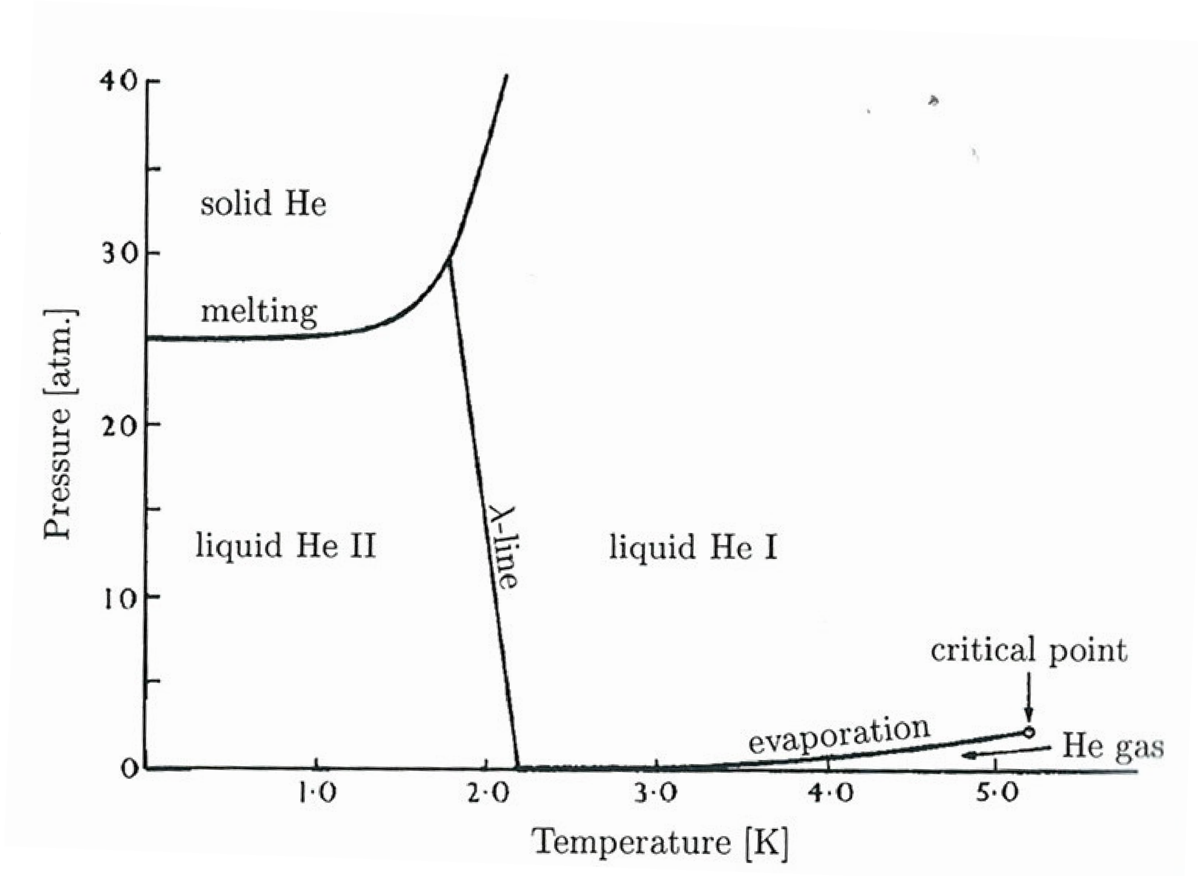
Condensation fraction versus T

1938: superfluidity in liquid helium first manifestation of BEC

liquid phase => dense system
<interatom. distance> a few Å
typical range of interat. forces

T_λ = 2.17 K
T_C = 3.1 K (BEC transition for ideal Bose gas model at the same density)

strong interaction between He atoms => only 10% of atoms in the same quantum state

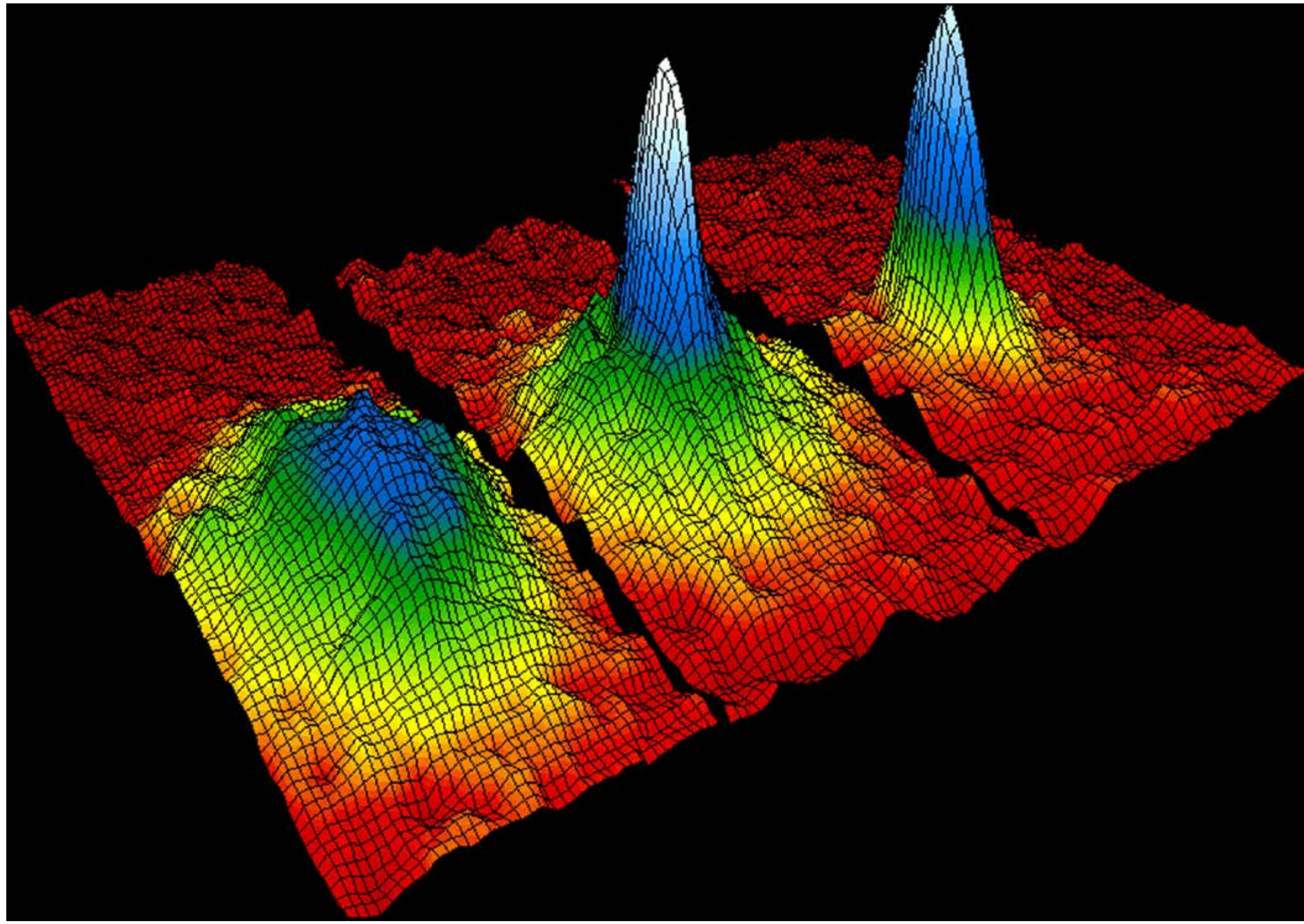


1995: atomic gases trapped vapours of ^{87}Rb and ^{23}Na

by combining the ≠

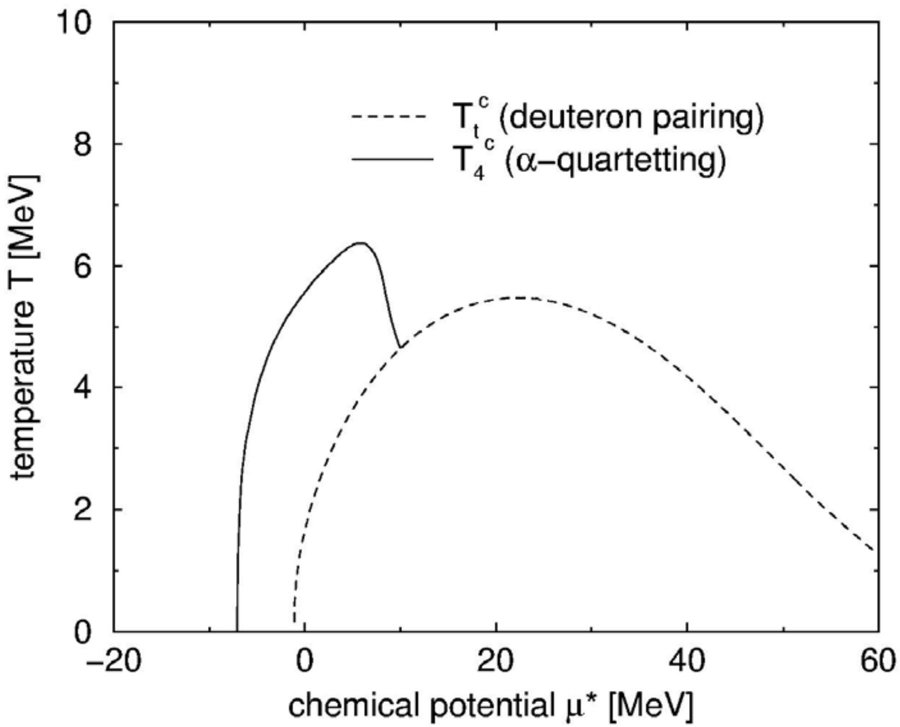
cooling techniques

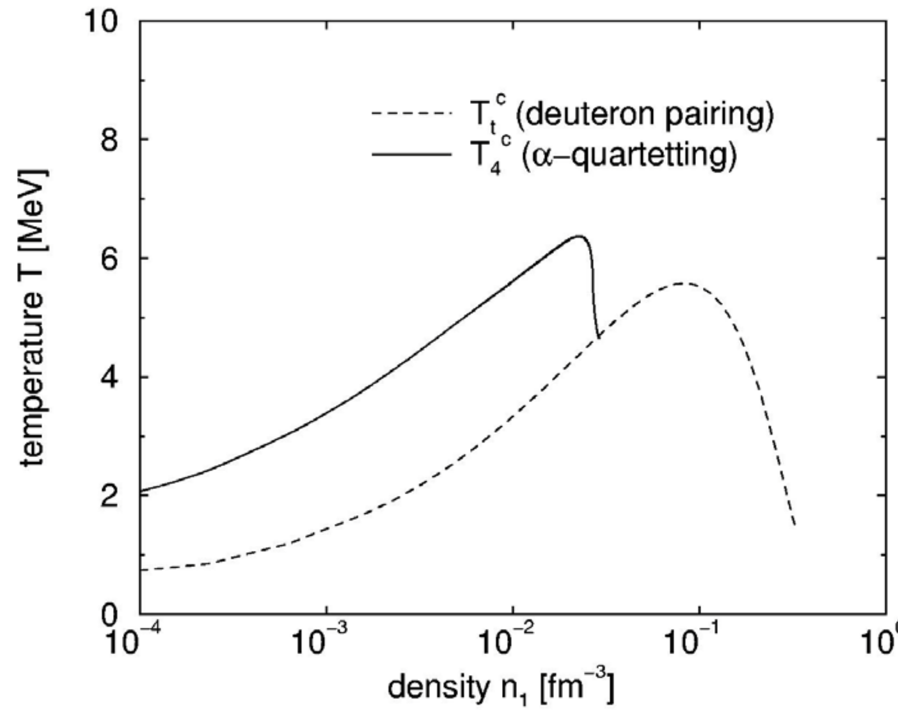
T and density required to observe BEC



optical density versus position: atom velocities around 0 in the center

Nuclear clusters in the medium symmetric nuclear matter





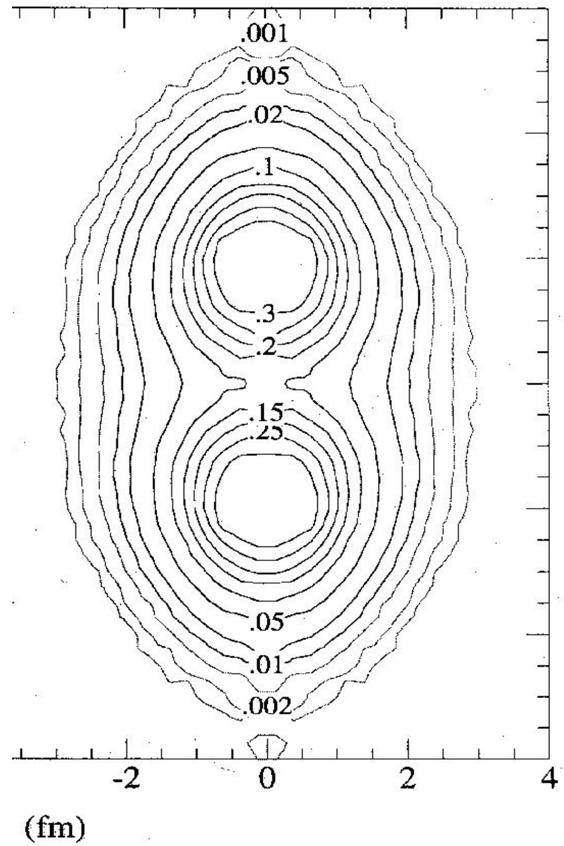
Condensation only at very low density

G. Ropke et al., PRL 80 (1998) 3177

Finite nuclei: ^{8}Be, ^{12}C …

Constant density contours

Quantum Monte Carlo calculation for ^{8}Be (0^{+})



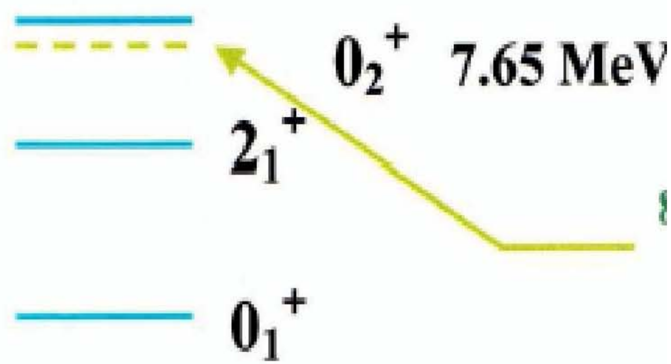
Density: $\rho_0/3$

R. B. Wiringa et al., PRC 62 (2000) 014001

$^{12}C^*$:Hoyle state

Role in the creation of ^{12}C in stellar nucleosynthesis

Does a dilute 3α $^{12}C^*$ state exist ?
Similar to $^{8}Be + \alpha$?



←Hoyle state

7.27 MeV
3 α threshold

Predictions: F. Hoyle et al., Phys. Rev. 92 (1953) 1095

Observation: C. W. Cook, W. A. Fowler et al., Phys. Rev. 107 (1957) 508

Shell model calculations

The most modern no-core shell model calculations predict the 0_2^+ at around 17 MeV excitation energy

2 α's in 1S orbit, 1 in 2S
2 α's in 1S orbit, 1 in 1D
3 α's in 1S orbit

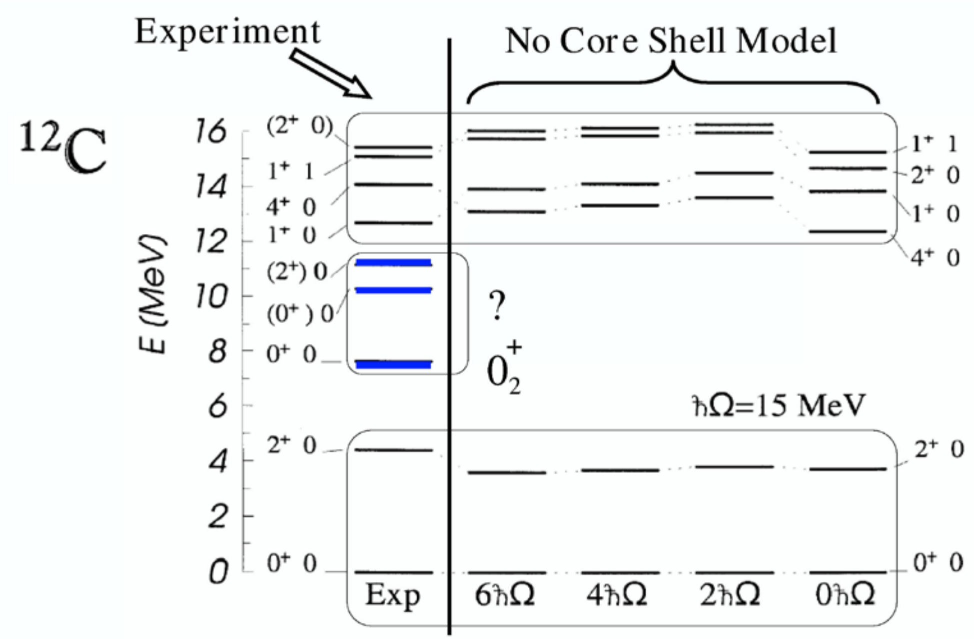


Figure 4. *Experimental and NCSM excitation spectra for ^{12}C for different model space sizes.*

it seems impossible to get Hoyle state from shell model calculation !

A. Tohsaki et al., PRL 87 (2001) 192501

Alpha cluster wave function

Theoretical Description

Ideal Bose condensate : $|0\rangle = b_0^\dagger b_0^\dagger \cdots b_0^\dagger |vac\rangle$

α-particle condensate : $|\Phi_{\alpha C}\rangle = C_\alpha^\dagger C_\alpha^\dagger \cdots C_\alpha^\dagger |vac\rangle$

In r-space :

$$\langle \vec{r}_1, \vec{r}_2, \cdots, \vec{r}_{4n} | \Phi_{\alpha C}\rangle = \mathcal{A}\left\{\Phi(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4)\Phi(\vec{r}_5,\vec{r}_6,\vec{r}_7,\vec{r}_8)\cdots\Phi(\vec{r}_{4n-3},\vec{r}_{4n-2},\vec{r}_{4n-1},\vec{r}_{4n})\right\}$$

A: antisymmetrizer

In comparison with pairing :

$$\langle \vec{r}_1, \vec{r}_2, \cdots | BCS\rangle = \mathcal{A}\left\{\Phi(\vec{r}_1,\vec{r}_2)\Phi(\vec{r}_3,\vec{r}_4)\cdots\right\}$$

Variational ansatz for $\Phi(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4)$: $\Phi(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4) = e^{-\frac{2}{B^2}\vec{R}^2}\phi_\alpha(\vec{r}_i - \vec{r}_j)$

Center of mass : $\vec{R} = \frac{1}{4}(\vec{r}_1 + \vec{r}_2 + \vec{r}_3 + \vec{r}_4)$

Intrinsic α-wave function :

$$\phi_\alpha(\vec{r}_i - \vec{r}_j) = e^{-\frac{1}{8b^2}\left\{(\vec{r}_4-\vec{r}_1)^2 + (\vec{r}_4-\vec{r}_2)^2 + (\vec{r}_4-\vec{r}_3)^2 + \cdots\right\}}$$

Two variational parameters : B, b

Two limits : $B = b$ $\quad |\Phi_{\alpha C}\rangle =$ Slater determinant

$B \gg b$ $\quad |\Phi_{\alpha C}\rangle =$ gas of independent α-particles

Two dimensional surface : $E(B,b) = \dfrac{\langle \Phi_{\alpha C}|H|\Phi_{\alpha C}\rangle}{\langle \Phi_{\alpha C}|\Phi_{\alpha C}\rangle}$

A. Tohsaki et al., PRL 87 (2001) 192501

Alpha cluster wave function

Quantization of energy surface E (B ,b) :

Force : A. Tohsaki 1990 no adjustable parameters !

Without adjustable parameters:

^{12}C: $E(0_2^+) - E_{thr}$ = theory +0.50 MeV
exp. +0.38 MeV

^{16}O: $E(0_5^+) - E_{thr}$ = theory -0.70 MeV
exp. -0.44 MeV

$E(0_6^+) - E_{thr}$ = theory + 2.0 MeV
exp. + 0.66 MeV

Rms radii calculated => $\rho_0/3$

Y. Fusaki et al., PRL 101 (2008) 082502

$^{12}C^*$:Hoyle state

momentum distribution of the a particles for 0_1^+ and 0_2^+ states

Reflecting the dilute structure of the Hoyle state => strong concentration of the momentum distribution in the k<1fm

Id dilute neutral atomic condensate states at very low temperature.

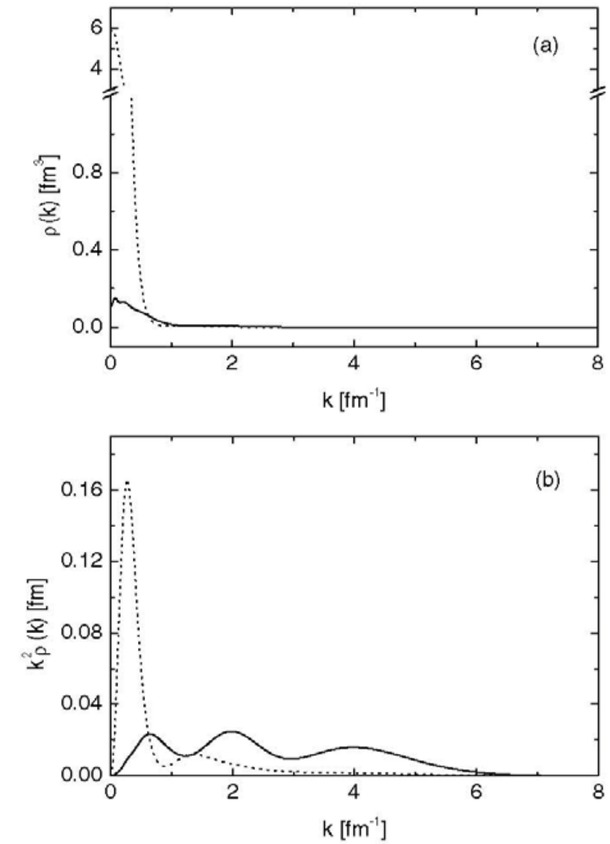


Fig. 7. Momentum distribution of the α particle, (a) $\rho(k)$ and (b) $k^2 \times \rho(k)$, for the 0_1^+ (solid line) and 0_2^+ (dotted line) states.

T. Yamada and P. Schuck EPJA 26 (2005) 185

Hoyle state: almost ideal α-particle condensate (70%)

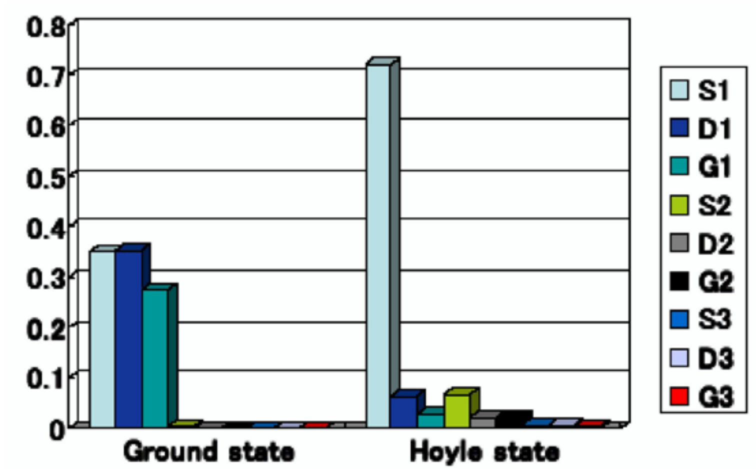
Boson occupancy :

α-particle density matrix :

$$\rho_\alpha(\vec{R},\vec{R}'), \quad \vec{R} \ : \ \text{c.m. of } \alpha$$

Diagonalization :

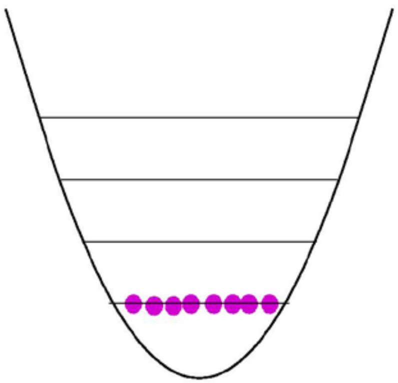
$$^{12}C : \quad O_2^+ \qquad 70\% \quad \text{S-wave occupancy}$$



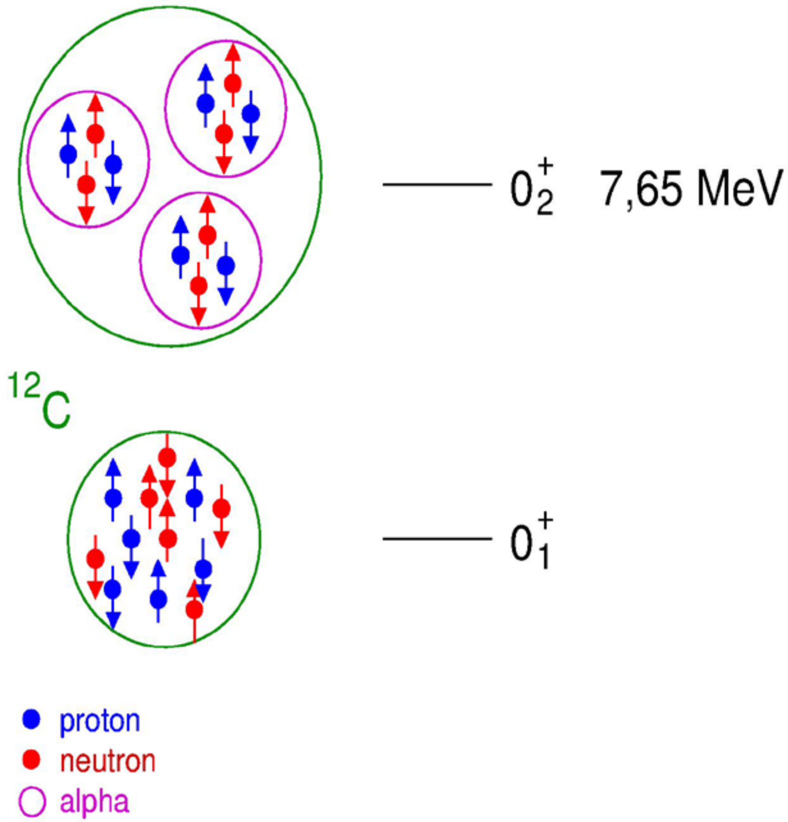
T. Yamada and P. Schuck, EPJA 26 (2005) 185

From ^{12}C to n alphas

Bosons

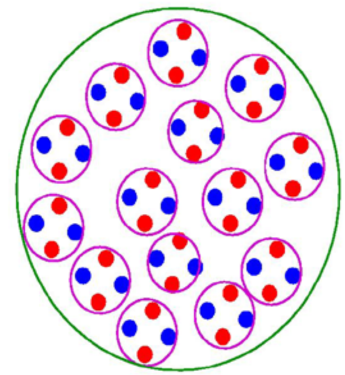


Back to nuclei



many α's

condensate

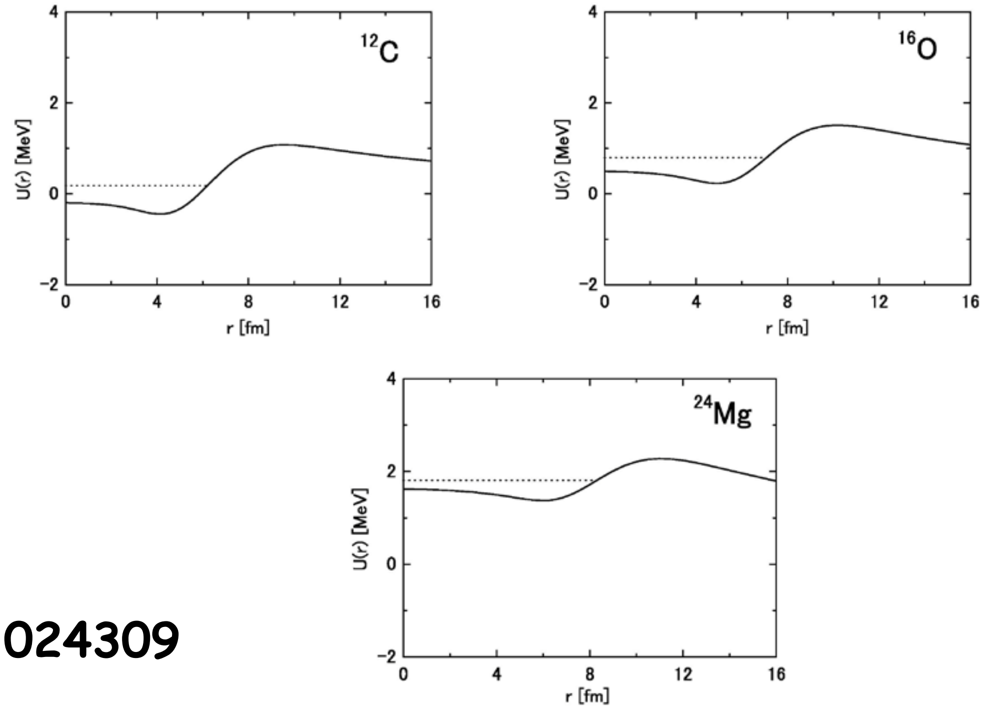


strong cluster phenomena in lighter nuclei

Alpha particle mean field potential

Calculations done with approximation for nα >4

Estimate: maximum of 8-10 αs together in a condensate



T. Yamada and P. Schuck PRC 69 (2004) 024309

Experimental strategy

We search for a simultaneous emission of low (*C:126 keV, *O:165 keV) and equal energy alphas close to the Na threshold

intermediate energy HI reactions to take advantage of fragment velocity boosts associated with high granularity of detection

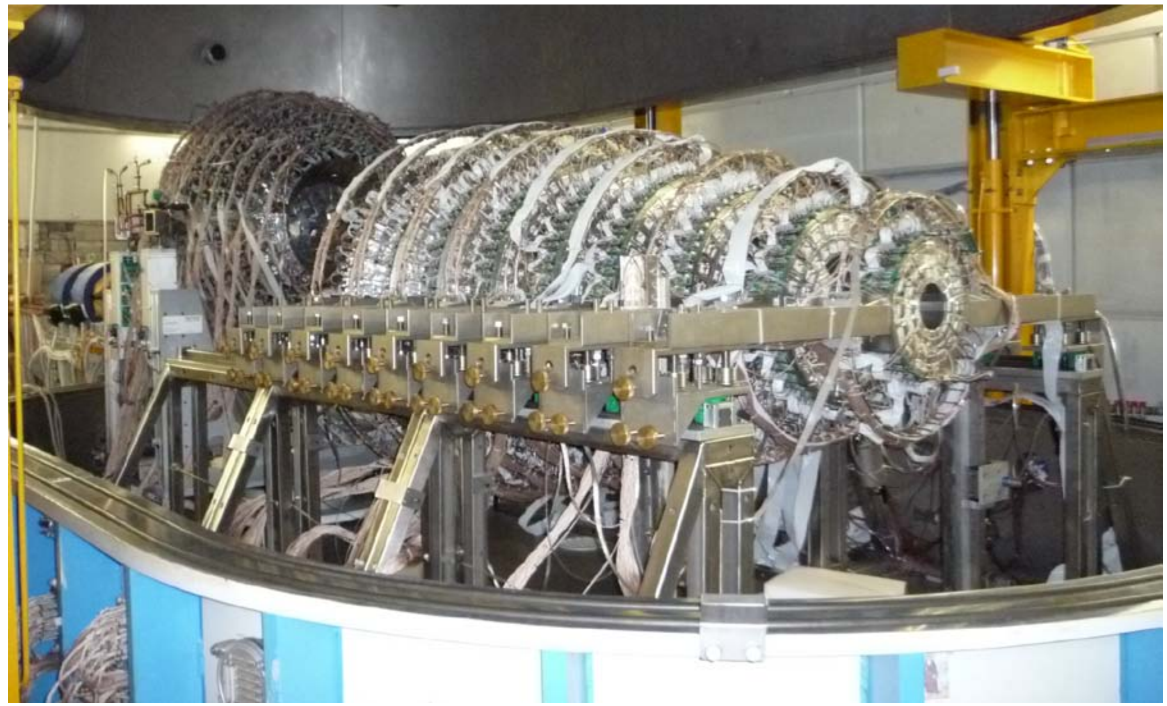
➔ $^{40}Ca + {}^{12}C$ at 25 MeV per nucleon

and use of powerful multi-particle correlation methods

CHIMERA multidetector
1192 Si-CsI(Tl) telescopes

26 rings covering 95 % of 4π
from 1^{o} to 176^{o}
very high granularity at forward angles

thickness:
Si ≈ 300 μm
CsI(Tl) from 12 to 3 cm



CHIMERA experiment

$^{12}C^*$, $^{16}O^*$: secondary products of quasi-projectile deexcitations

Identification
- E-TOF: A up to 20
- E-ΔE: Z and A up to 20
- Fast-Slow CsI(Tl): Z≤5 and associated A

Energy calibration
- Z=1: proton beams in Si, CsI(Tl)
- Z=2: dedicated energy calibration of CsI(Tl) from TOF
- Z>2: E from Si information (C and O beams)

CsI(Tl) resolution: 1 – 2 %

CHIMERA experiment

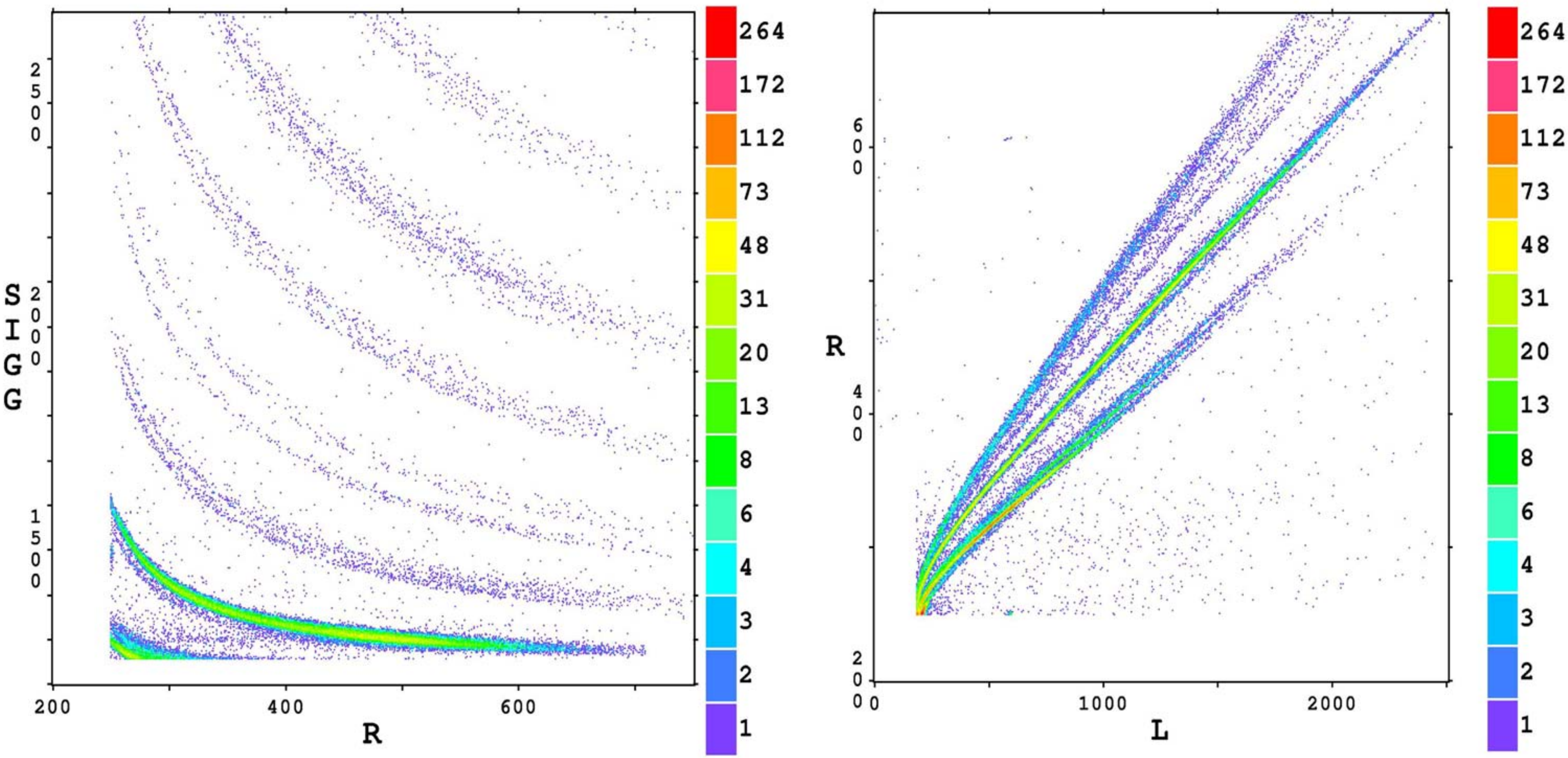
$^{12}C^*$, $^{16}O^*$: secondary products of quasi-projectile deexcitations

- Beam intensity: 10^7 ions/s
- Angular range used: Θ=1-62°

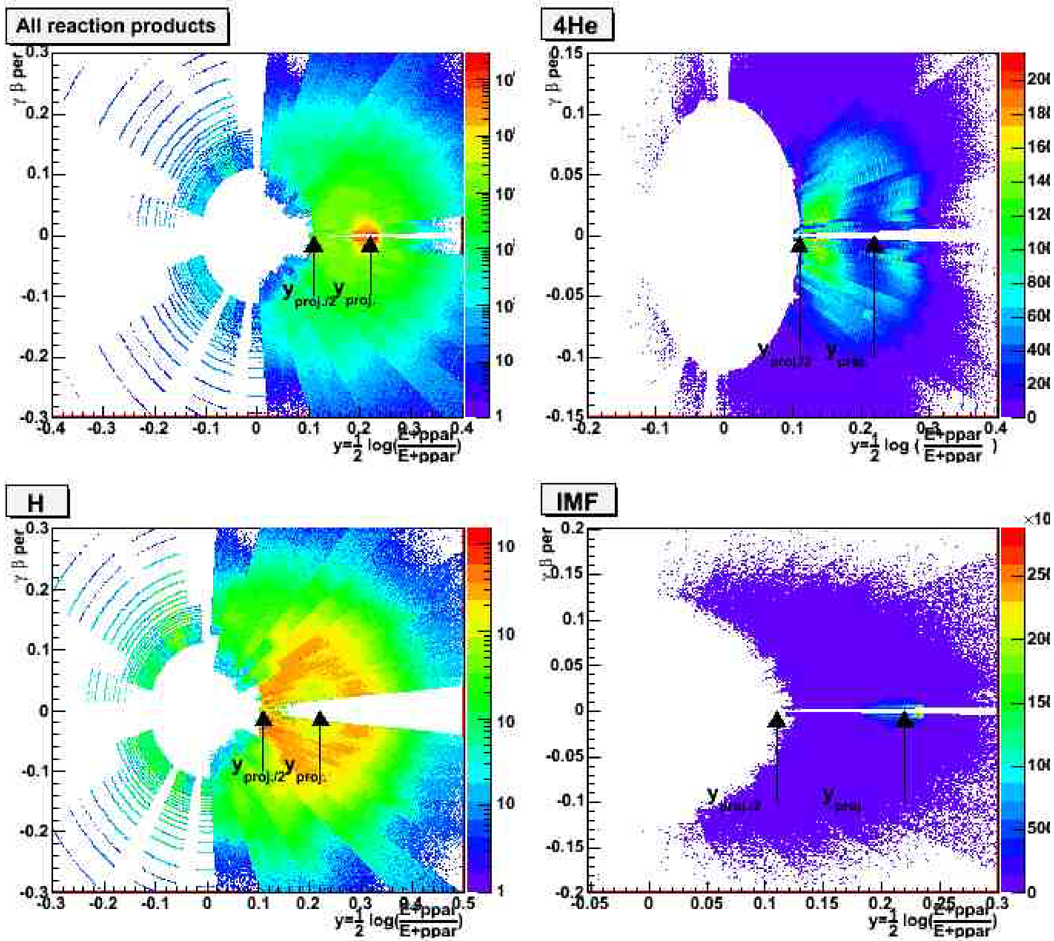
  (rings 1-9 + small part of the sphere)

=> 816 telescopes

Particle identification



Source identification



Multi-particle correlation function

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

Alpha particles emitted in the forward part of the cm frame (quasi projectiles)

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

Correlation function:

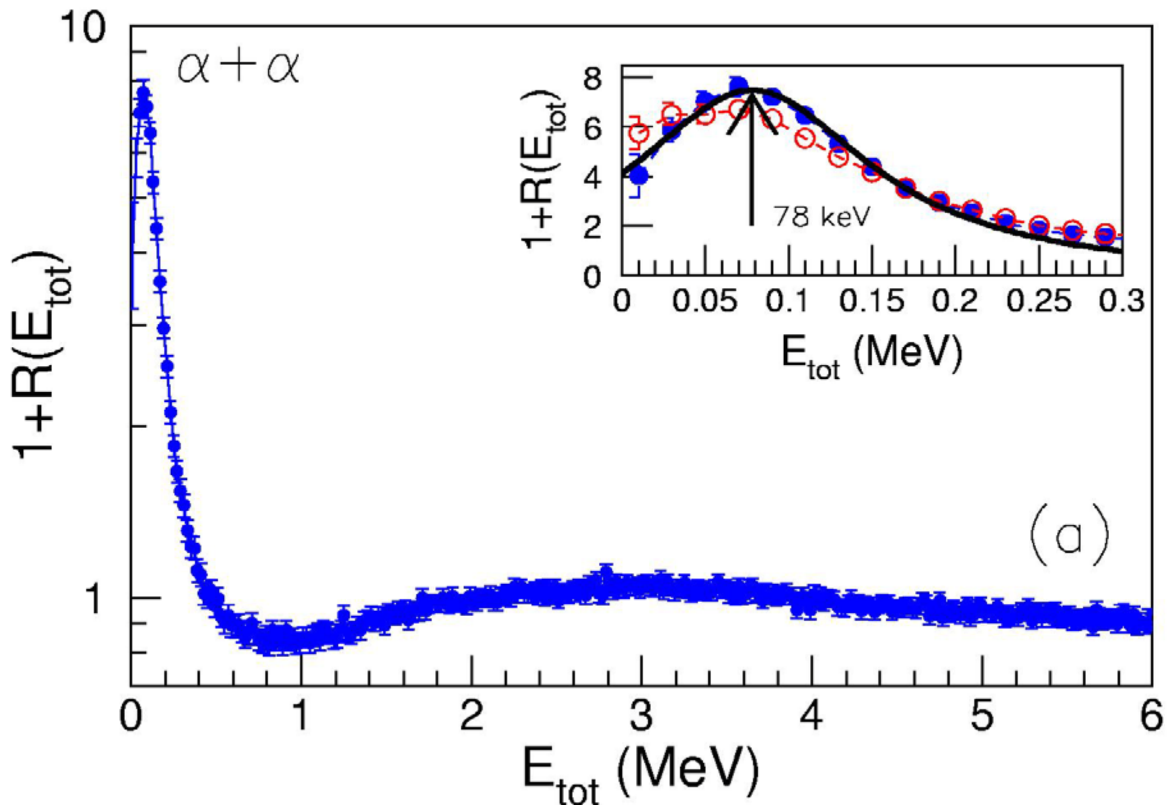
$$1+R(E_{tot})=Ycorr(E_{tot})/Yuncorr(E_{tot})$$

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



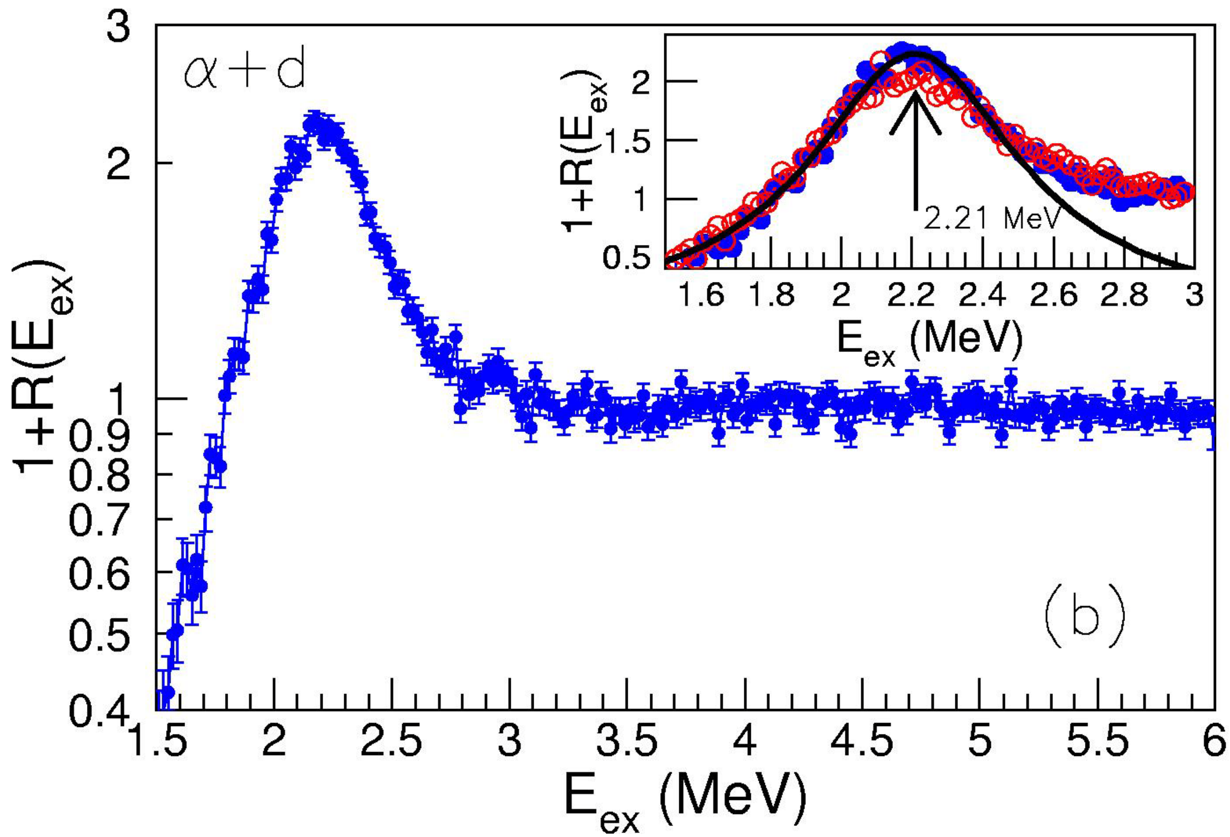
Quality of energy calibration ?
d-alpha correlations

^6Li

$E_{ex}=E_{tot}-Q$

$E_{ex}=$ 2.186 MeV

Exp: 2.21 MeV



three-alpha correlation function

$M_\alpha=3$

$^{12}C \rightarrow \alpha+\alpha+\alpha$

$\rightarrow \alpha+{}^{8}Be \rightarrow \alpha+\alpha+\alpha$

Yuncorr(Ek):

Alphas in different events

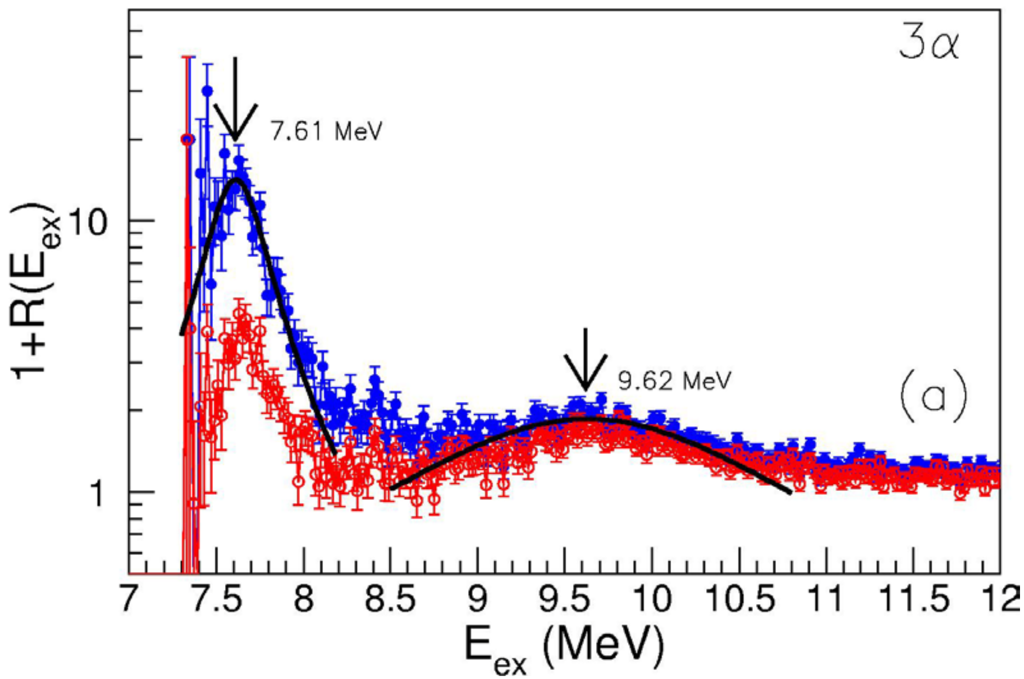
2 alphas in the same event

Qualitative info (detection dependent)

3α threshold
7.275 MeV

$E_{ex}=E_{tot}-Q$

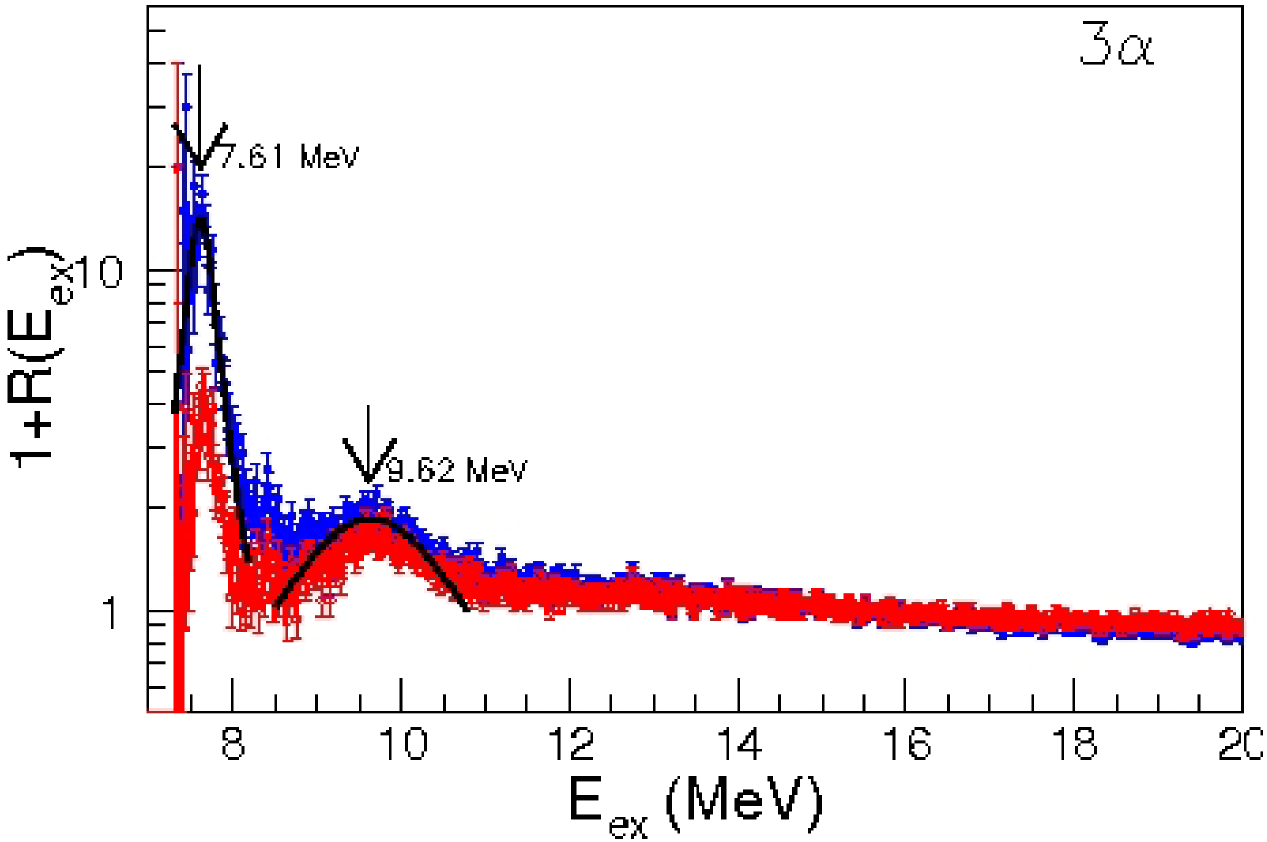
^{12}C second 0^+
7.654 MeV
Γ=8.5 eV
E_{tot}=379 keV



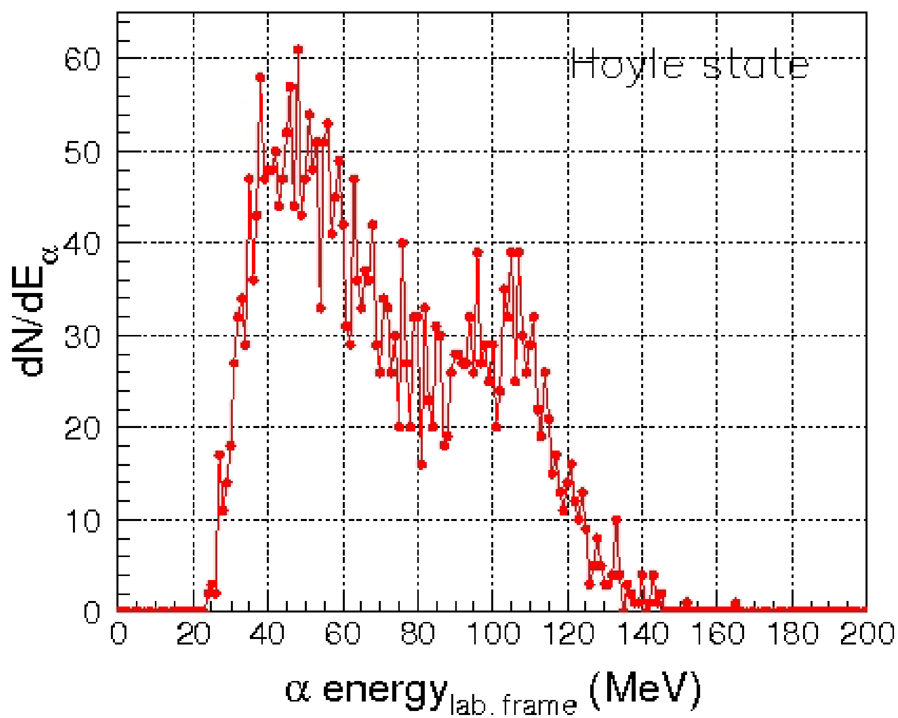
3^- 9.641 MeV (34keV)
2_2^+ 9.7 MeV (?)
0_3^+ 10.3 MeV (3MeV)

PRL soumis

three-alpha correlation function



12C*-Hoyle state: energy in the lab of the alpha particles



Intra-event correlation function

G. Tabacaru et al., EPJA 18 (2003) 103

For a given alpha multiplicity, 2 intra-event parameters:

average kinetic energy $\langle E\alpha \rangle$

root mean square $\sigma_{E\alpha}$

Correlation function:

$$1+R(\sigma_{E\alpha}, \langle E\alpha \rangle) = Ycorr(\sigma_{E\alpha}, \langle E\alpha \rangle) / Yuncorr(\sigma_{E\alpha}, \langle E\alpha \rangle)$$

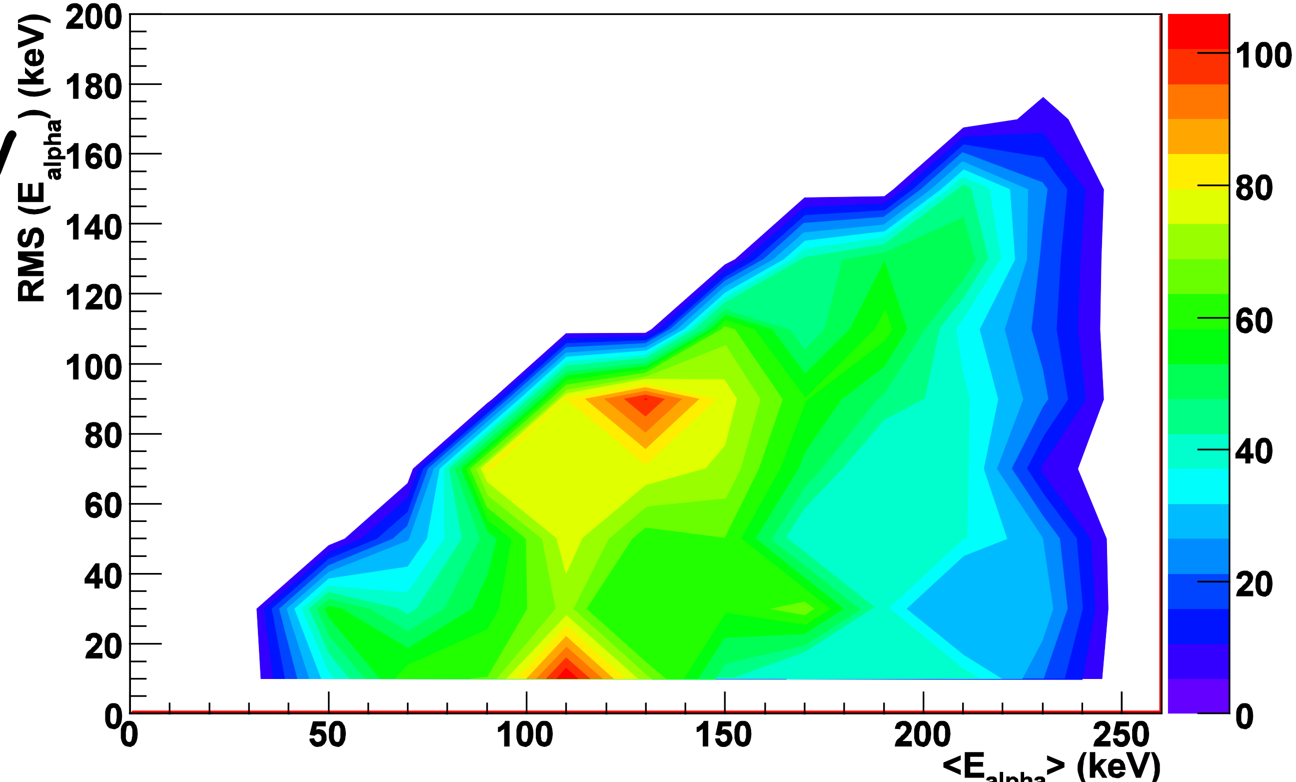
12C*-Hoyle state: BEC state

Mα=3

7.37 ≤ Eex ≤ 7.97 MeV

39 events
<Eα> ≈ 110 keV
σ ≤ 25 keV

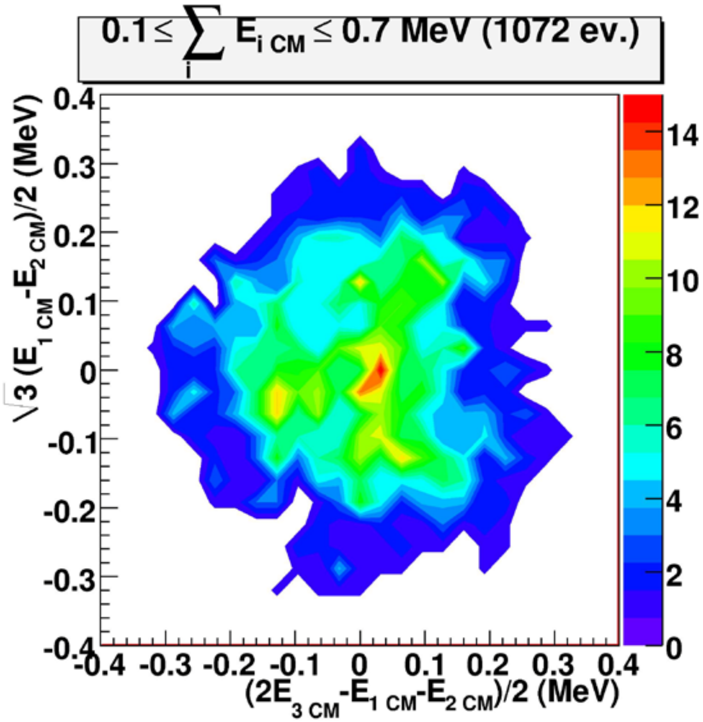
85 events
<Eα> ≈ 130 keV
σ ≈ 85 keV



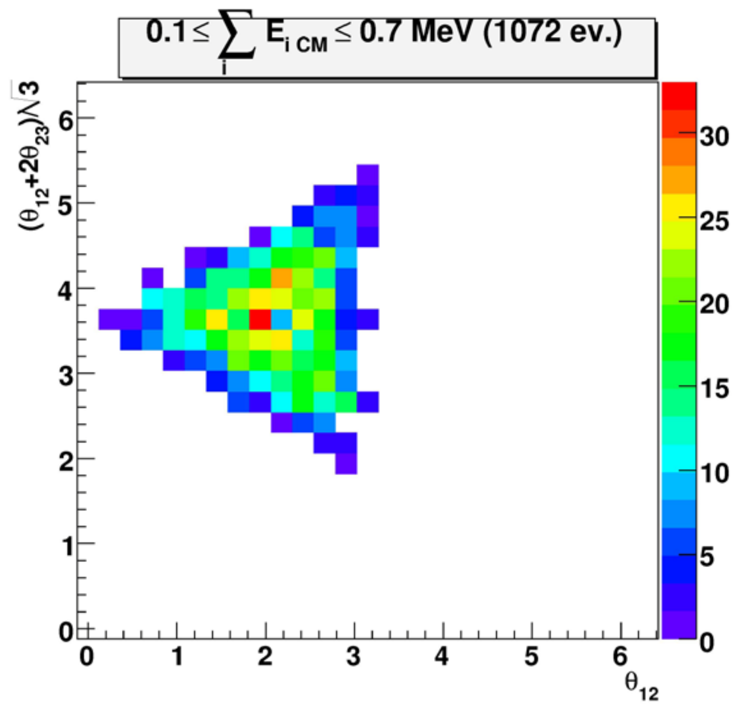
PRL soumis

12C*-Hoyle state: BEC state
« Dalitz plots »

energy



angle



three-alpha correlation function

$M_\alpha=3$

$^{12}C \rightarrow \alpha+\alpha+\alpha$

$\rightarrow \alpha+{}^{8}Be \rightarrow \alpha+\alpha+\alpha$

Yuncorr(Ek):

Alphas in different events

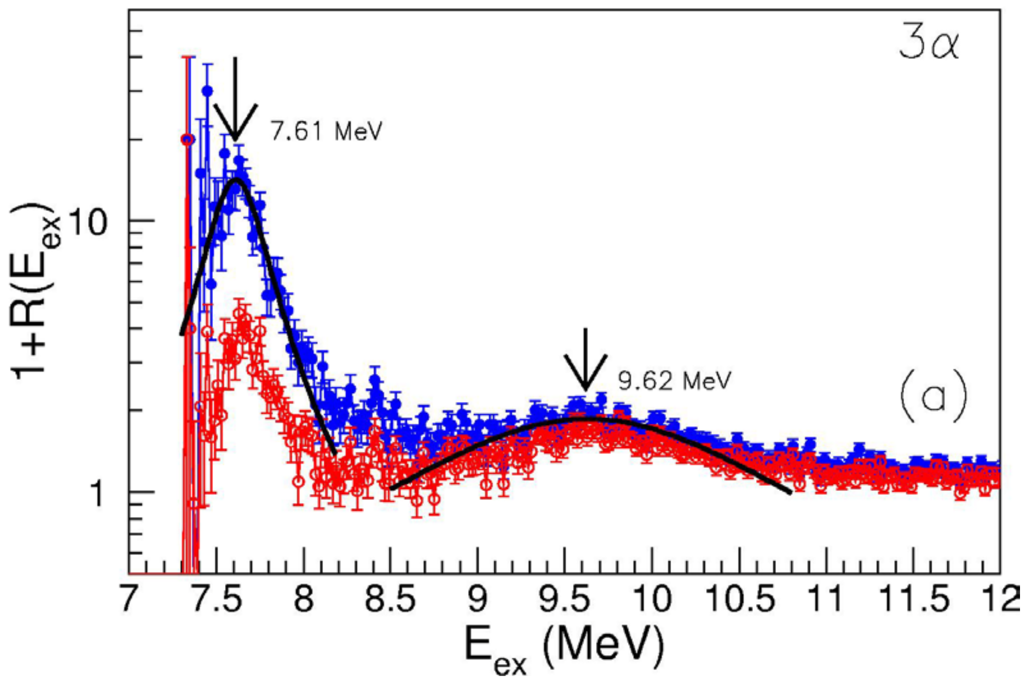
2 alphas in the same event

Qualitative info (detection dependent)

3α threshold
7.275 MeV

$E_{ex}=E_{tot}-Q$

^{12}C second 0^+
7.654 MeV
Γ=8.5 eV
E_{tot}=379 keV

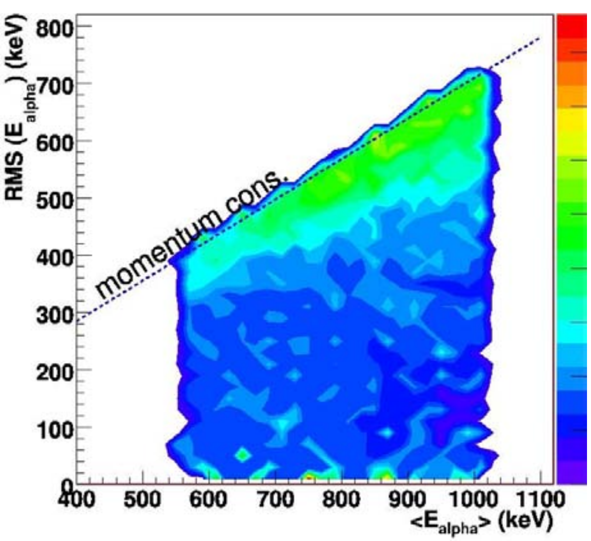


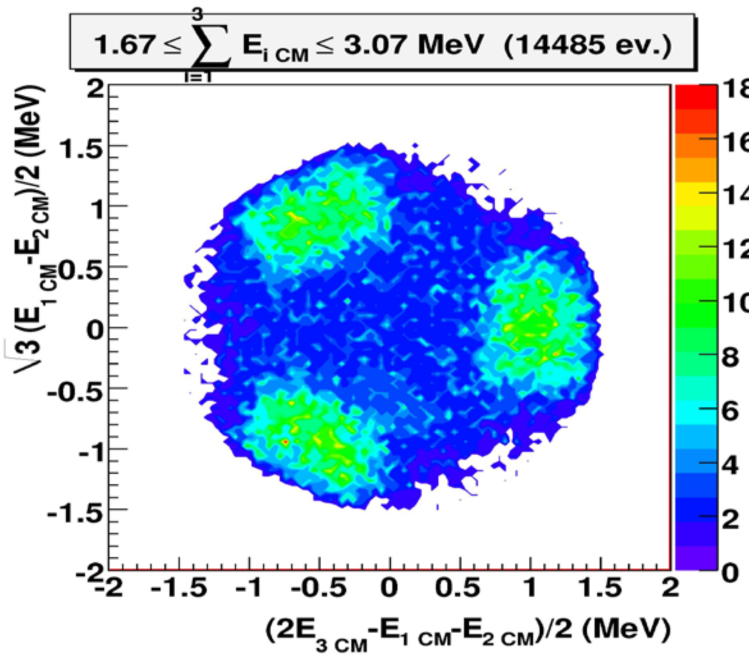
3^- 9.641 MeV (34keV)
2_2^+ 9.7 MeV (?)
0_3^+ 10.3 MeV (3MeV)

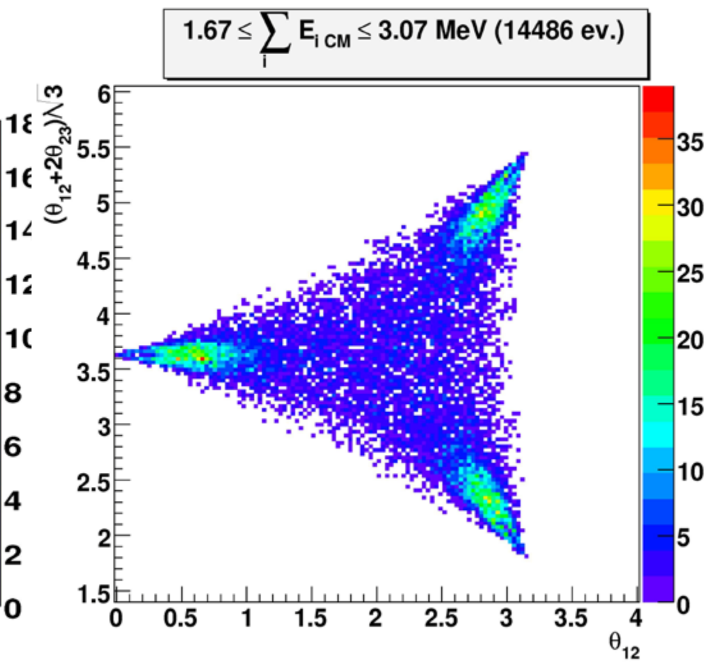
PRL soumis

$^{12}C^*$-broad peak at E_{ex} = 9.62 MeV

Intra-ev. corr. funct. Energy Dalitz plot Angle Dalitz plot







$^{12}C^* \rightarrow \alpha + {}^{8}Be \rightarrow \alpha + \alpha + \alpha$

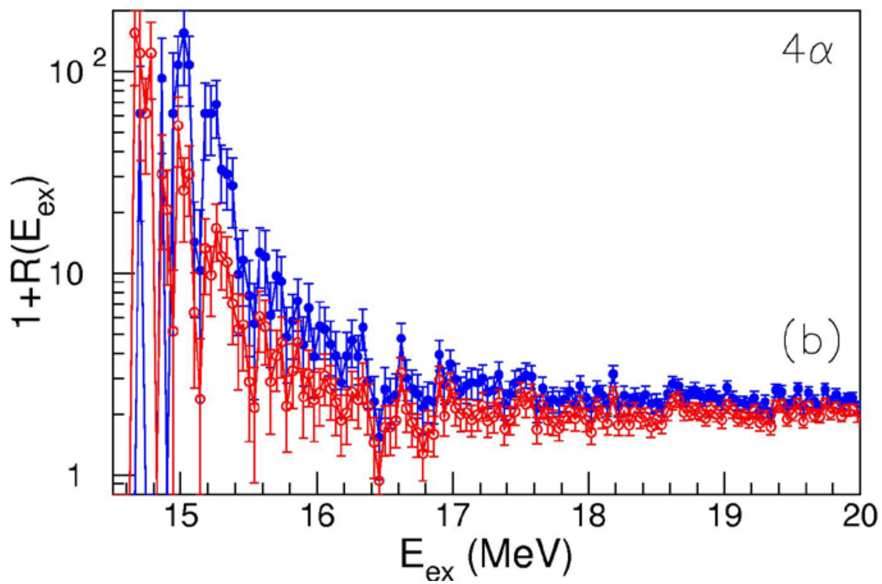
four-alpha correlation function

$M_\alpha >= 4$

Yuncorr(Ek):
Alphas in different events
2 alphas in the same event
+ 3 alphas in the same event
+ 2 alphas in 2 different events

^{16}O sixth 0^+
15.097 MeV
Γ=166 keV
E_{tot}=660 keV

4α threshold
14.437 MeV



$^8Be+^8Be$ threshold 14.619 MeV

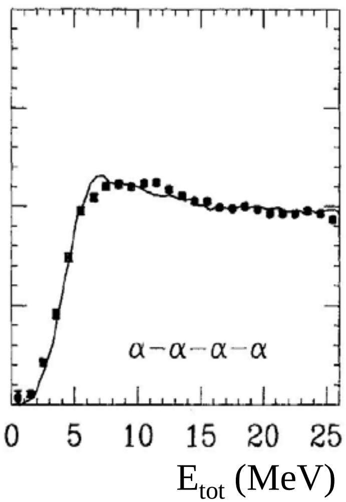
$^{12}C + \alpha$ threshold 14.811 MeV

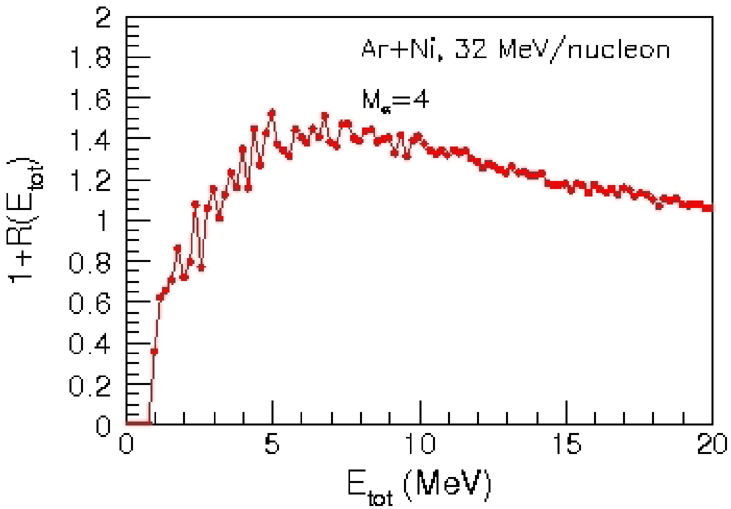
four-alpha correlation function

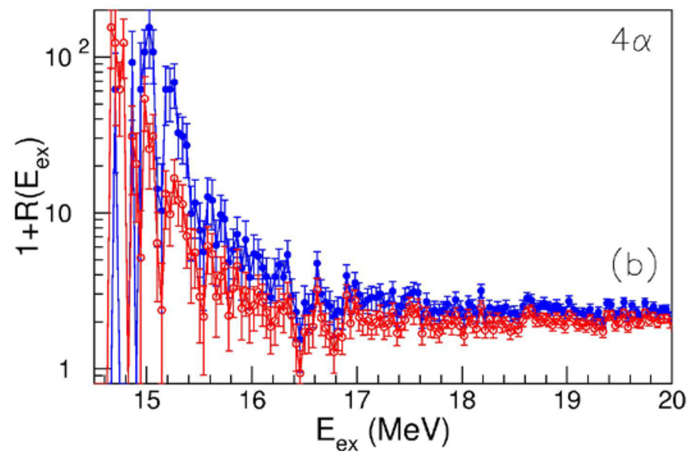
$^{20}Ne+^{120}Sn$ 40 MeV/nucleon

INDRA

CHIMERA







$E_{ex}=E_{tot} - Q$

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

Conclusion and perspectives

Heavy ion collisions used to produce ^{12}C and ^{16}O excited states theoretically predicted as BEC states.

39 events of low energy RMS corresponding to the direct decay of the Hoyle state have been identified as a signature of BEC in nuclei.

Only 4 events corresponding to the deexcitation of the 6th 0^+ state of ^{16}O.

Granularity of CHIMERA good enough for such a study. A new experiment with higher statistics is planned to better study the ^{16}O case. Simulations are needed to say if heavier « BEC nuclei » can be studied with CHIMERA.