Nuclear Alpha-Particle Condensation

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

First experimental evidence of alpha-particle condensation for the Hoyle state
Ad. R. Raduta, B. Borderie, N. Le Neindre, E. Geraci, P. Napolitani, M.F. Rivet et al.
Outline of the talk

- Condensation in the nuclear physics context
- Experimental strategy and experiment
- Results
- Conclusions and perspectives
Nuclear clusters in the medium symmetric nuclear matter

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

Condensation only at very low density $\rho < \rho_0/5$
Finite nuclei: $^8\text{Be}$, $^{12}\text{C}$ ...

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

Density: $\rho_0/3$

R. B. Wiringa et al., PRC 62 (2000) 014001
$^{12}\text{C}^*$: Hoyle state

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

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

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


Hoyle state

7.27 MeV

3 $\alpha$ threshold
Shell model calculations

The most modern no-core shell model calculations predict the $O_2^+$ 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

A. Tohsaki et al., PRL 87 (2001) 192501
Alpha cluster wave function and formalism of ideal Bose condensate

Theoretical Description

Ideal Bose condensate: \( |0\rangle = b_0^\dagger b_0^\dagger \ldots b_n^\dagger |vac\rangle \)

\( \Phi_{ac} \): \( |\Phi_{ac}\rangle = C_a C_b \ldots C_n |vac\rangle \)

\( \alpha \)-particle condensate: \( |\Phi_{ac}\rangle = C_1 \ldots C_{\alpha} |vac\rangle \)

Variational ansatz for \( \Phi(\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4) : \Phi(\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4) = e^{\frac{-\beta^2R^2}{2}} \phi(\vec{r}_1 - \vec{r}_2) \)

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

Intrinsic \( \alpha \)-wave function:

\[ \phi(\vec{r}_1 - \vec{r}_2) = e^{-\frac{1}{8\rho}(r_1^2 + r_2^2 + (r_3 - r_2)^2 + r_4^2 + \ldots)} \]

Two variational parameters: \( B, b \)

Two limits: \( B = b \) | \( \Phi_{ac} \rangle = \text{Slater determinant} \)

\( B \gg b \) | \( \Phi_{ac} \rangle = \text{gas of independent } \alpha \text{-particles} \)

Two dimensional surface: \( E(B, b) = \frac{\langle \Phi_{ac} | H | \Phi_{ac} \rangle}{\langle \Phi_{ac} | \Phi_{ac} \rangle} \)

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

BEC LEA nov. 2010

Bernard Borderie
**Alpha cluster wave function**

Quantization of energy surface $E(B,b)$:

Force: A. Tohsaki 1990 no adjustable parameters!

Without adjustable parameters:

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

exp. $+0.38 \text{ MeV}$

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

exp. $-0.44 \text{ MeV}$

$E(0^+_6) - E_{\text{thr}} = \text{theory } +2.0 \text{ MeV}$

exp. $+0.66 \text{ MeV}$

Rms radii calculated $\Rightarrow \rho_0/3$

Y. Fusaki et al., PRL 101 (2008) 082502
$^{12}\text{C}^*$: Hoyle state

Momentum distribution of the $\alpha$ particles for $0_1^+$ and $0_2^+$ states

Reflecting the dilute structure of the Hoyle state $\Rightarrow$ strong concentration of the momentum distribution in the $k<1\text{fm}^{-1}$.

Id dilute neutral atomic condensate states at very low temperature.

T. Yamada and P. Schuck EPJA 26 (2005) 185
Hoyle state: almost ideal $\alpha$-particle condensate (70%)

residual correlations among $\alpha$ particles (mostly of the Pauli type)

*Boson occupancy:*

$\alpha$-particle density matrix:

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

Diagonalization:

$^{12}C$:  $O_2^+$ 70% S-wave occupancy

T. Yamada and P. Schuck, EPJA 26 (2005) 185
From $^{12}\text{C}$ to $n$ alphas

Bosons

Back to nuclei

Many $\alpha$'s condensate

$^{12}\text{C}$

$0^+_1$ 7.65 MeV
Alpha particle mean field potential

Calculations done with approximation for $n_\alpha > 4$

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

Experimental strategy

We search for a simultaneous emission of low 
\((^{12}\text{C}:126\text{ keV}, \ ^{16}\text{O}:165\text{ keV})\) and equal energy alphas close to the \(\text{Na}\) threshold

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

\[ {^{40}\text{Ca} + ^{12}\text{C}} \text{ at } 25\text{ MeV per nucleon} \]

and use of powerful multi-particle correlation methods to select excited states and their deexcitations
CHIMERA multidetector
1192 Si-CsI(Tl) telescopes

26 rings covering 95% of $4\pi$
from 1° to 176°
very high granularity at forward angles

thickness:
Si $\approx$ 300 µm
CsI(Tl) from 12 to 3 cm
CHIMERA experiment

$^{12}\text{C}^\ast$, $^{16}\text{O}^\ast$: mostly secondary products of quasi-projectile deexcitations

Identification
- E-TOF: A up to 20
- E-$\Delta$E: 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: 1.5 – 2 %
CHIMERA experiment

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

- Beam intensity: $10^7$ ions/s
- Angular range used: $\Theta=1-62$
  (rings 1-9 + small part of the sphere)

=> 816 telescopes
Particle identification
Selection: reaction products with velocities $> \frac{v_{\text{proj}}}{2}$
Multi-particle correlation function
R. Charity et al., PRC 52 (1995) 3126

to identify and select nuclei/excited states

\[ N \text{ alphas} \Rightarrow \text{determination of the alpha} \]
\[ \text{emitter reference frame} \Rightarrow E_{tot} = \sum E_k \]

Correlation function:
\[ 1 + R(E_{tot}) = \frac{Y_{corr}(E_{tot})}{Y_{uncorr}(E_{tot})} \]
Quality of energy calibration?

Two-alpha correlation function

$^8\text{Be}$

$E_{\text{tot}}=92$ keV ($\Gamma=5.6$ 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

$^6\text{Li}$

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

$E_{ex} = 2.186 \text{ MeV}$

Exp: $2.21 \text{ MeV}$
three-alpha correlation function

\[ M_\alpha = 3 \]

\[ ^{12}\text{C} \rightarrow \alpha + \alpha + \alpha \]

\[ \rightarrow \alpha + ^8\text{Be} \rightarrow \alpha + \alpha + \alpha \]

Yuncorr(E_k):

Alphas in different events
2 alphas in the same event

3\alpha\text{ threshold} 
7.275 MeV

\[ E_{ex} = E_{tot} - Q \]

\[ ^{12}\text{C} \text{ second } 0^+ \]
7.654 MeV 
\[ \Gamma = 8.5 \text{ eV} \]
\[ E_{tot} = 379 \text{ keV} \]

3\text{-} 9.641 \text{ MeV (34keV)}
2_2^+ \ 9.7 \text{ MeV (74keV)}
0_3^+ \ 10.3 \text{ MeV (3MeV)}

PRL soumis
arXiv:1004.3234

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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:

\[
1 + R(\sigma_{E_\alpha}, \langle E_\alpha \rangle) = Y_{corr}(\sigma_{E_\alpha}, \langle E_\alpha \rangle)/Y_{uncorr}(\sigma_{E_\alpha}, \langle E_\alpha \rangle)
\]
$^{12}\text{C}^*$-Hoyle state: alpha cond. state

$M\alpha=3$

$7.37 \leq E_{ex} \leq 7.97\text{ MeV}$

39 events

$\langle E\alpha \rangle \approx 110\text{ keV}$

$\sigma \leq 25\text{ keV}$

85 (241) events

$\langle E\alpha \rangle \approx 130\text{ keV}$

$\sigma \approx 85\text{ keV}$

PRL soumis, arXiv:1004.3234
12C*-Hoyle state: alpha cond. state
« Dalitz plots »

energy

Angle (new Dalitz)

PRL soumis, arXiv:1004.3234

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three-alpha correlation function

$M_\alpha = 3$

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

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

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

$^{12}\text{C}$ second $0^+$

7.654 MeV

$\Gamma = 8.5 \text{ eV}$

$E_{\text{tot}} = 379 \text{ keV}$

Yuncorr($E_k$):

Alphas in different events

2 alphas in the same event

Qualitative info (detection dependent)

$^2\text{He}$

9.641 MeV (34 keV)

$^2_2\text{Be}$

9.7 MeV (?)

$^3_0\text{He}$

10.3 MeV (3 MeV)
$^{12}\text{C}^*$-broad peak at $E_{\text{ex}} = 9.62$ MeV

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

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

SOTANCP2 2010 arXiv:1009.1267
four-alpha correlation function

\[ M_{\alpha} \geq 4 \]

\(^{16}\text{O}\) sixth \(0^+\)
15.097 MeV
\(\Gamma = 166\) keV
\(E_{\text{tot}} = 660\) keV

4\(\alpha\) threshold
14.437 MeV

\(^{8}\text{Be} + ^{8}\text{Be}\) threshold 14.619 MeV

\(^{12}\text{C} +\alpha\) threshold 14.811 MeV

\(Y_{\text{uncorr}}(E_k)\):
Alphas in different events
+ 2 alphas in the same event
+ 3 alphas in the same event
+ 2 alphas in 2 different events
four-alpha correlation function

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

INDRA

CHIMERA

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

$E_{\text{ex}} = E_{\text{tot}} + 14.44\text{ MeV}$
Conclusion and perspectives

Heavy ion collisions used to produce $^{12}$C and $^{16}$O excited states theoretically predicted as alpha-particle condensed states.

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

A most interesting information for astrophysics would be the branching ratio between the two decay processes: A simulation is in progress to extract this ratio with an error bar. At present upper limit for direct 3-alpha decay: 4% (M. Freer et al., PRC 49 (1994) R1751). From phase space considerations $\Rightarrow 5 \times 10^{-4}$

Only 4 events (equal energy alphas) identified in the deexcitation region of the 6th $0^+$ state of $^{16}$O. Granularity of CHIMERA good enough for such a study. A new experiment with higher statistics must be performed to better study the $^{16}$O case. Simulations are needed to say if condensate states for heavier nuclei can be studied with CHIMERA.
12C*-Hoyle state: BEC state

No selection (2.5 million ev.)
12C*-Hoyle state: BEC state

denominator: a+a+a
four-alpha correlation function
INDRA data, Ar+Ni 32 AMeV 
granularity too bad for 4α

\begin{align*}
\text{Ar+Ni, 32 MeV/nucleon} \\
M_s = 3 \\
two \alpha \text{ from the same event}
\end{align*}

\begin{align*}
\text{Ar+Ni, 32 MeV/nucleon} \\
M_s = 4 \\
two \alpha \text{ from the same event}
\end{align*}
3s and 3p correlation functions: numerator and denominator
<table>
<thead>
<tr>
<th>Ring</th>
<th>Module</th>
<th>Module DP2</th>
<th>Telescope</th>
<th>PID Si</th>
<th>Dist. (cm)</th>
<th>Θ</th>
<th>ΔΦ</th>
<th>ΔΩ</th>
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<td>1-E</td>
<td>16</td>
<td>1-16</td>
<td>0-15</td>
<td>4545-5560</td>
<td>350.</td>
<td>1.6-1.6</td>
<td>22.5</td>
<td>0.13</td>
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<tr>
<td>1-E</td>
<td>16</td>
<td>17-32</td>
<td>16-31</td>
<td>4561-5576</td>
<td>350.</td>
<td>1.6-2.6</td>
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<td>2-I</td>
<td>21</td>
<td>1-24</td>
<td>32-55</td>
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<td>2.6-3.6</td>
<td>15.</td>
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<td>25-48</td>
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<td>1-32</td>
<td>18-111</td>
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<td>4.6-5.8</td>
<td>11.25</td>
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<td>33-61</td>
<td>112-143</td>
<td>4657-6088</td>
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<td>1-40</td>
<td>144-183</td>
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<td>210.</td>
<td>7.8-9.5</td>
<td>9.</td>
<td>0.55</td>
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<td>4-E</td>
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<td>41-80</td>
<td>184-223</td>
<td>4728-5768</td>
<td>210.</td>
<td>8.5-10.</td>
<td>9.</td>
<td>0.66</td>
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<tr>
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<td>224-263</td>
<td>4769-5808</td>
<td>180.</td>
<td>10.11.5</td>
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<td>6-I</td>
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<td>1-48</td>
<td>301-351</td>
<td>4849-5896</td>
<td>160.</td>
<td>13.14.5</td>
<td>7.5</td>
<td>0.81</td>
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</table>

| 0.90 | 6-E  | 48     | 49-96    | 352-369 | 4897-4944 | 160. | 14.5-16. | 7.5   |
| 1.34 | 7-I  | 48     | 1-48    | 460-447 | 4945-5002 | 140. | 16.18.   | 7.5   |
| 1.49 | 7-E  | 48     | 49-96   | 448-595 | 4993-5040 | 140. | 18.20.   | 7.5   |
| 1.64 | 8-I  | 48     | 1-48    | 496-543 | 5041-5088 | 120. | 20.22.   | 7.5   |
| 1.78 | 8-E  | 48     | 49-96   | 544-591 | 5089-5136 | 120. | 22.24.   | 7.5   |
| 2.95 | 9-I  | 48     | 1-48    | 592-639 | 5137-5184 | 160. | 21.27.   | 7.5   |
| 3.27 | 9-E  | 48     | 49-96   | 640-687 | 5185-5232 | 160. | 27.30.   | 7.5   |

| 10   | 32    | 32     | 688-719 | -       | 40.  | 30.-38. | 11.2  |
| 11   | 32    | 32     | 720-751 | -       | 40.  | 38.-46. | 11.2  |
| 12   | 32    | 32     | 752-783 | -       | 40.  | 46.-54. | 11.2  |
| 13   | 32    | 32     | 784-815 | -       | 40.  | 54.-62. | 11.2  |
| 14   | 32    | 32     | 816-847 | -       | 40.  | 62.-70. | 11.2  |
| 15   | 32    | 32     | 848-879 | -       | 40.  | 70.-78. | 11.2  |
| 16   | 32    | 32     | 880-911 | -       | 40.  | 78.-86. | 11.2  |
| 17   | 32    | 32     | 912-943 | -       | 40.  | 86.-94. | 11.2  |