Nuclear Alpha-Particle Condensation

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

First experimental evidence of alpha-particle condensation for the Hoyle state

Bernard Borderie

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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

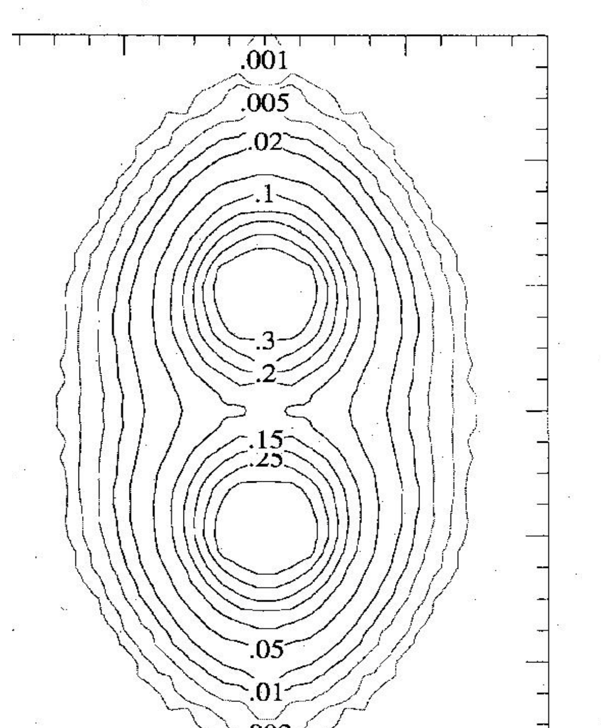
Condensation only at very low density
$\rho < \rho_0/5$

Finite nuclei: ^{8}Be, ^{12}C …

Constant density contours

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

Density: $\rho_0/3$



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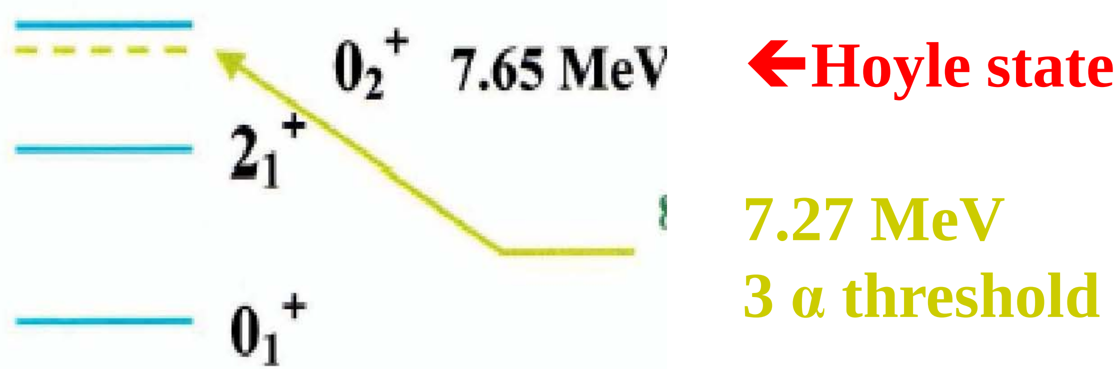
R. B. Wiringa et al., PRC 62 (2000) 014001

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

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

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



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

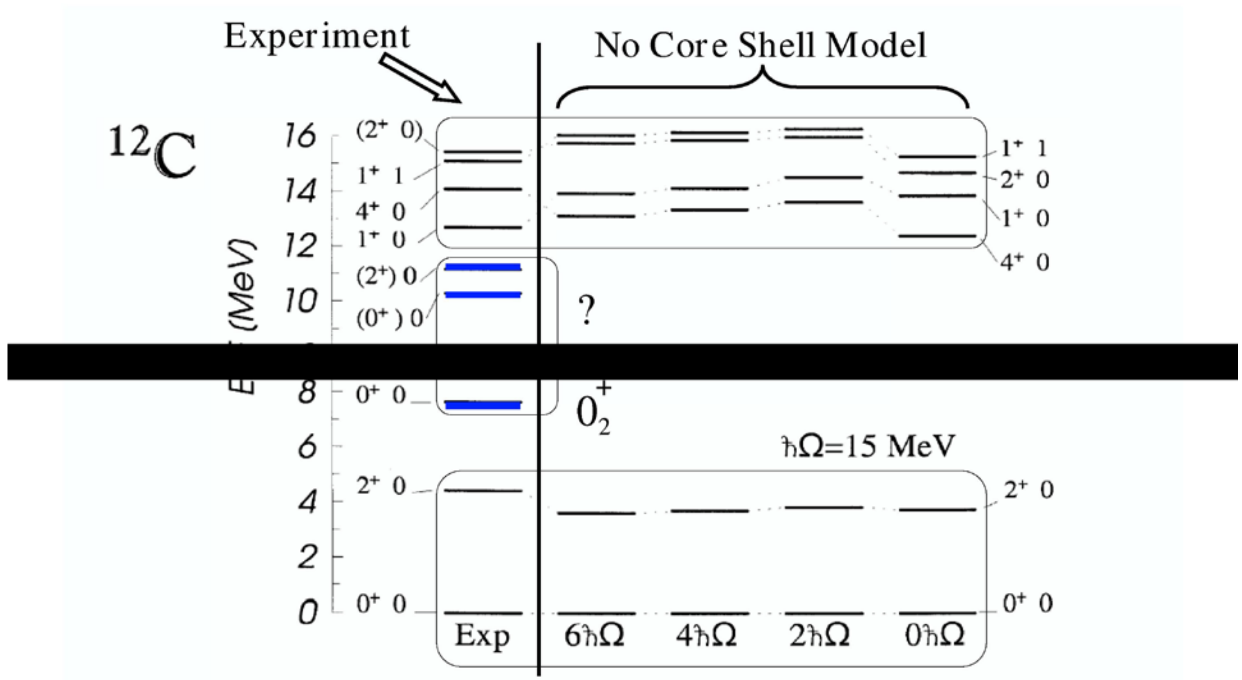


Figure 4. *Experimental and NCSM excitation spectra for ^{12}C for different model space sizes.*

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

Alpha cluster wave function and formalism of ideal Bose condensate

Theoretical Description

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

[redacted]

In r space :

A: antisymmetrizer

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

In comparison with pairing :

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 :

[redacted]

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 : $E(B,b) = \frac{\langle \Phi_{\alpha C} | H | \Phi_{\alpha C} \rangle}{\langle \Phi_{\alpha C} | \Phi_{\alpha C} \rangle}$

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^{-1}

Id dilute neutral atomic condensate states at very low temperature.

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

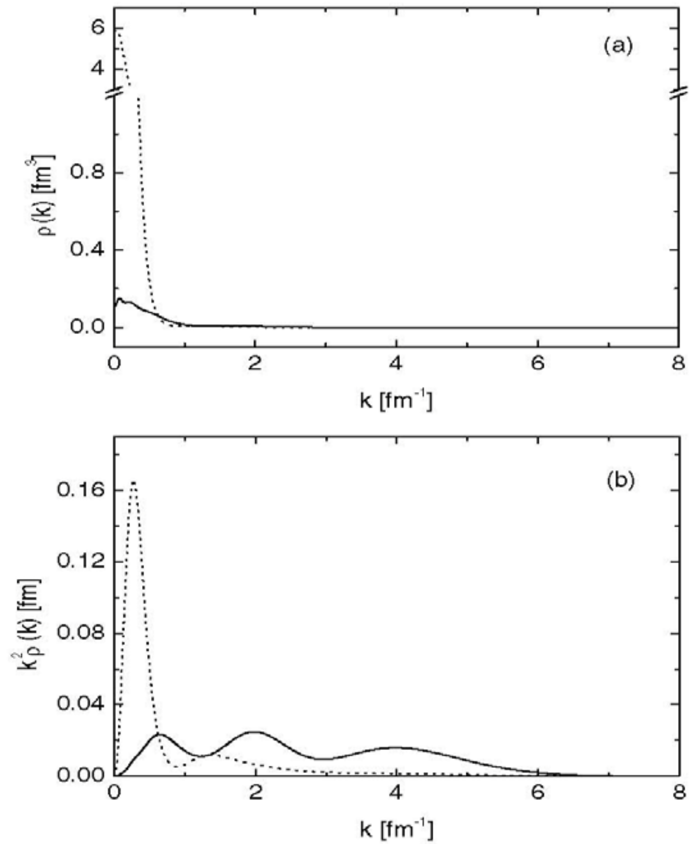


Fig. 7. Momentum distribution of the α particle, (a) $\rho(k)$ and (b) $k^2 \times \rho(k)$, for the 0_1^+ (solid line) and 0_2^+ (dotted line) states.

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

residual correlations among α particles (mostly of the Pauli type)

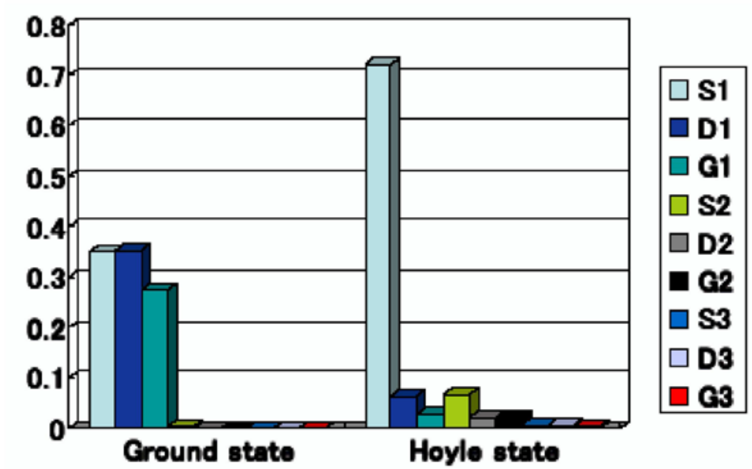
Boson occupancy :

α-particle density matrix :

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

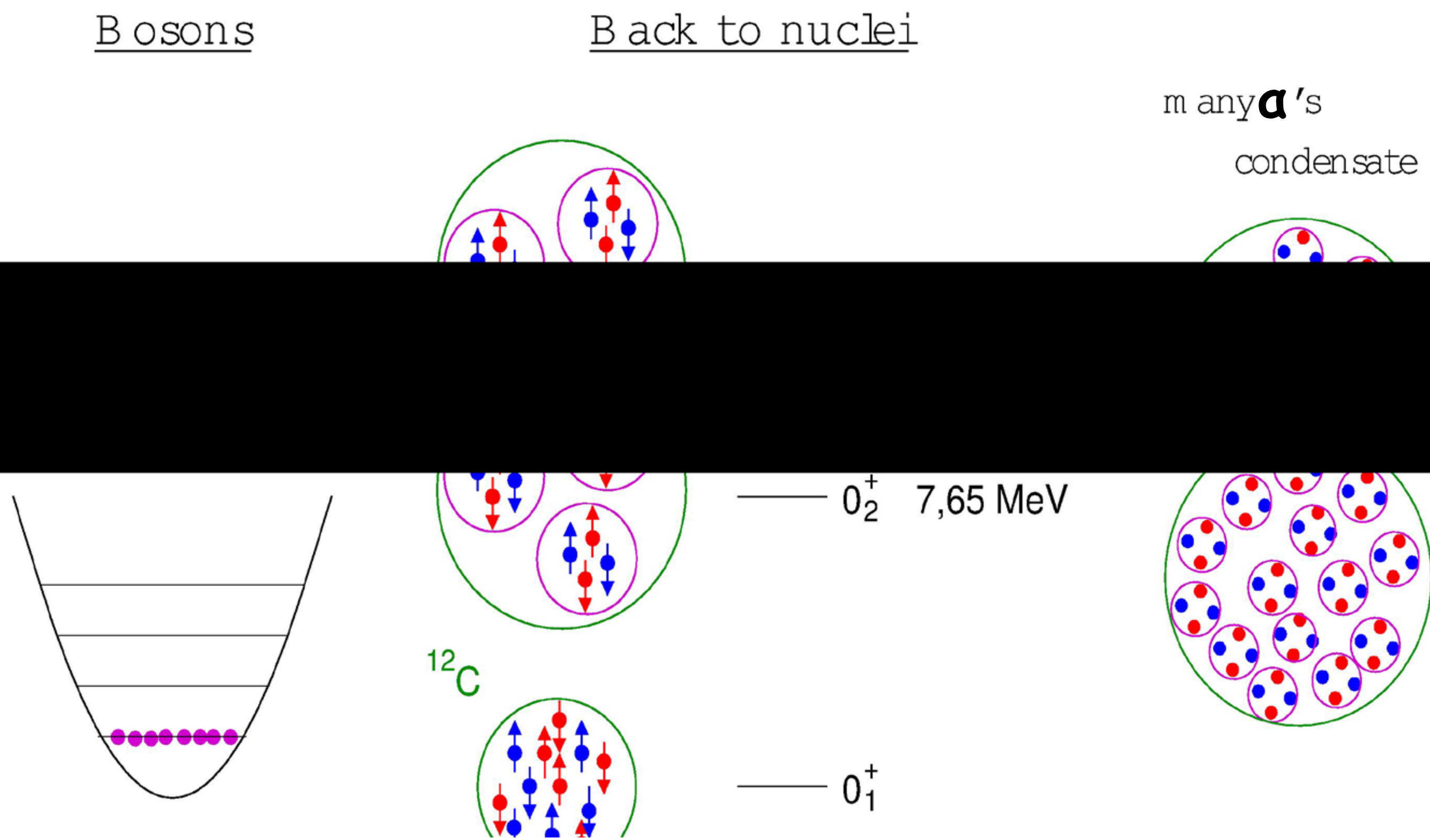
Diagonalization :

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



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

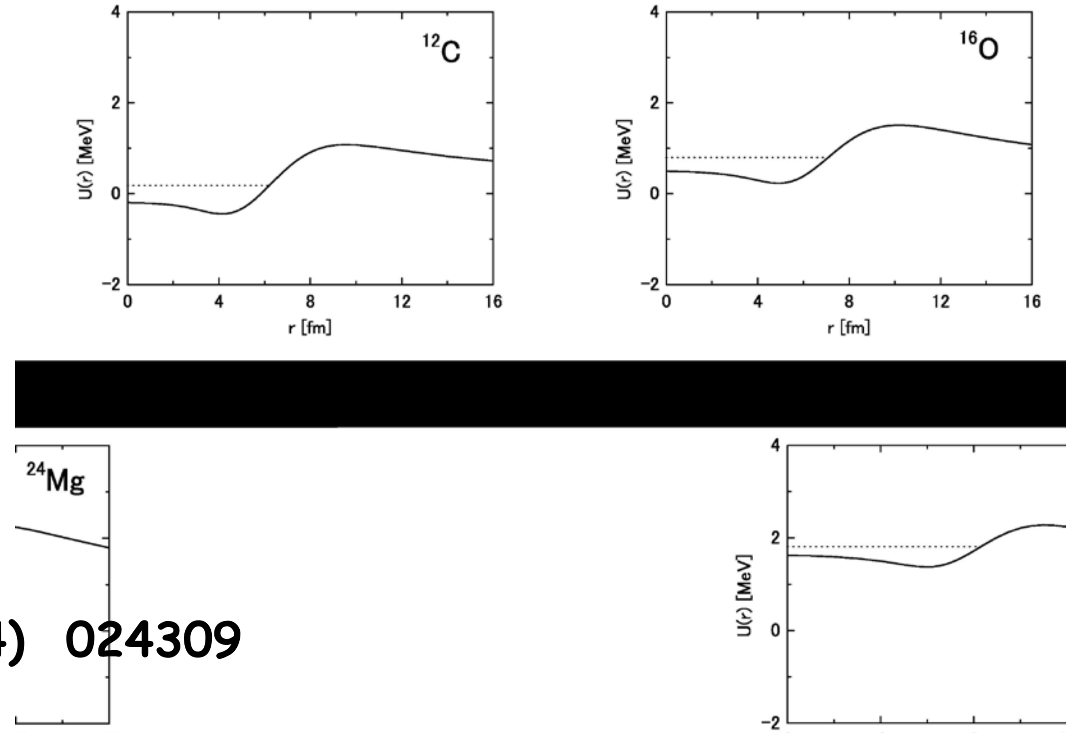
From ^{12}C to n alphas



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

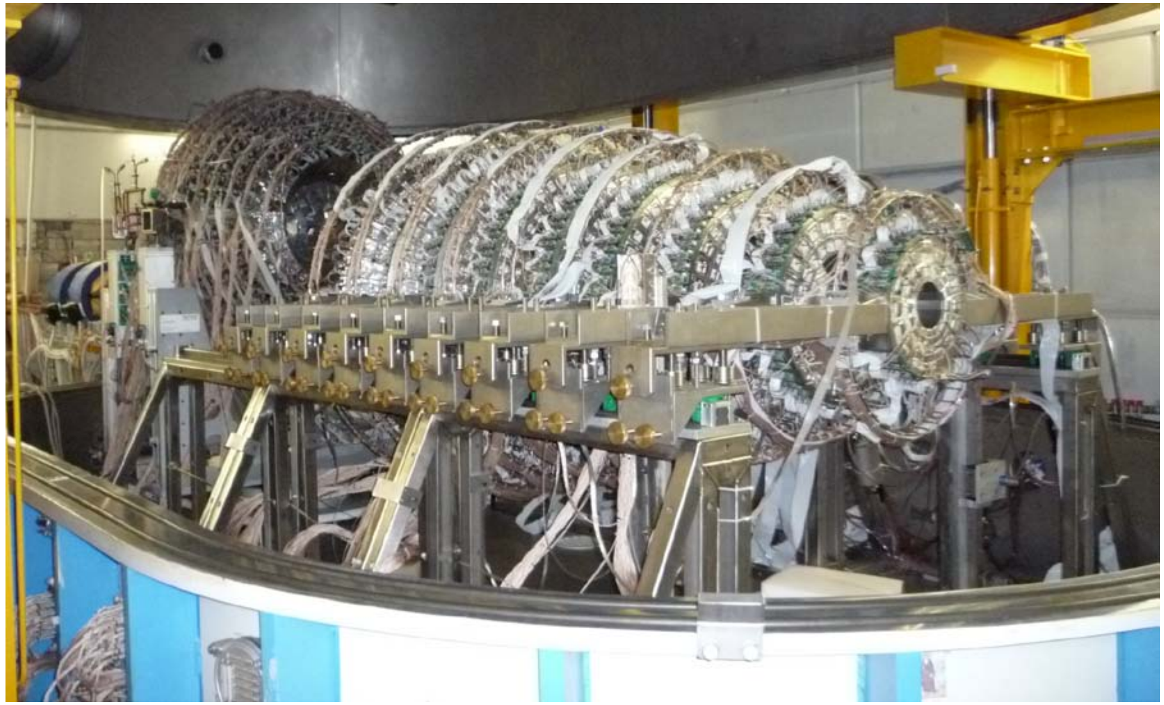
intermediate energy HI reactions to take advantage of fragment velocity boosts associated with high granularity of detection

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

and use of powerful multi-particle correlation methods to select excited states and their deexcitations

IPN Orsay

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

$^{12}C^*$, $^{16}O^*$: mostly 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: 1.5 – 2 %

CHIMERA experiment

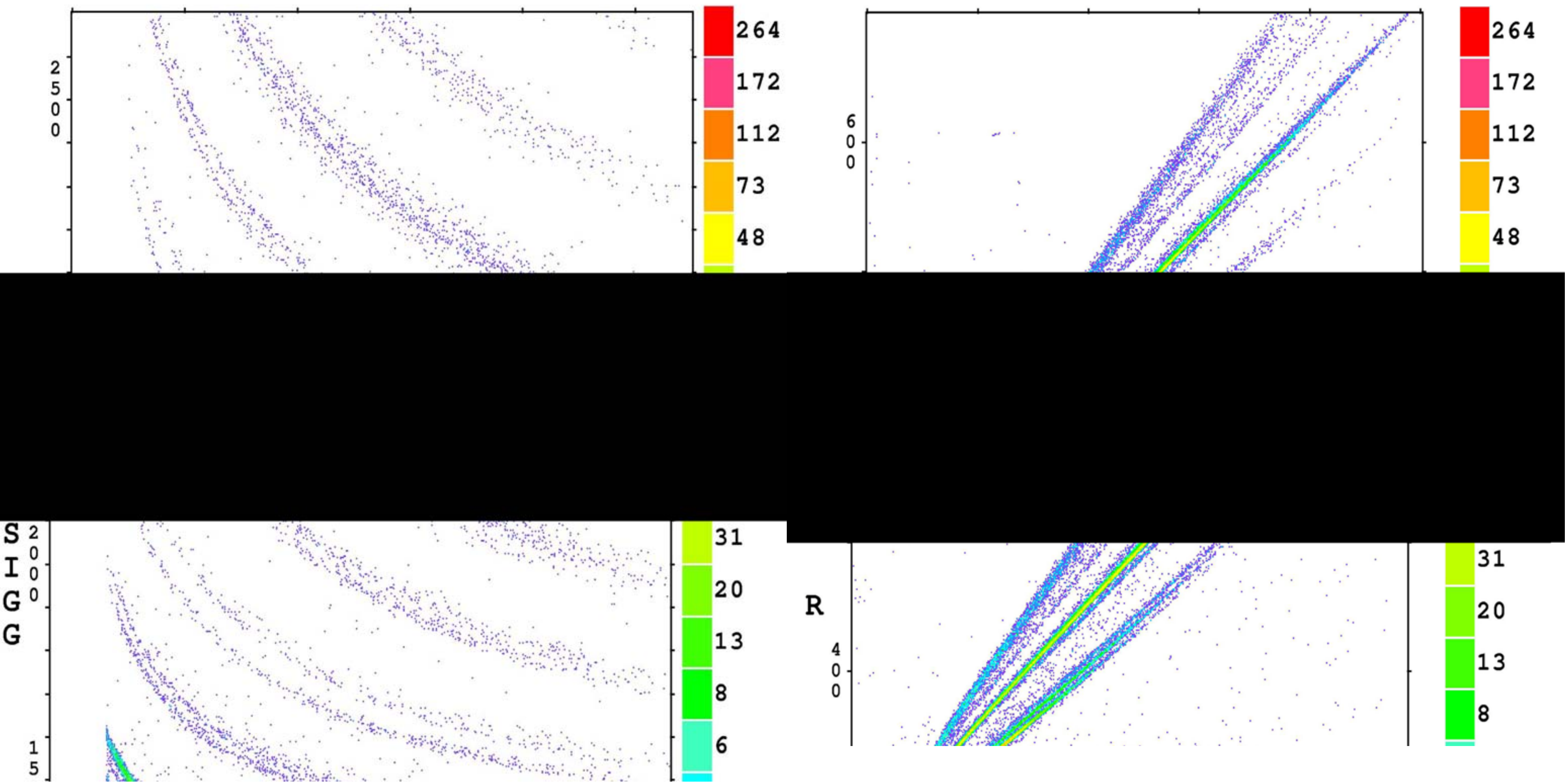
$^{12}C^*$, $^{16}O^*$: mostly secondary products of quasi-projectile deexcitations

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

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

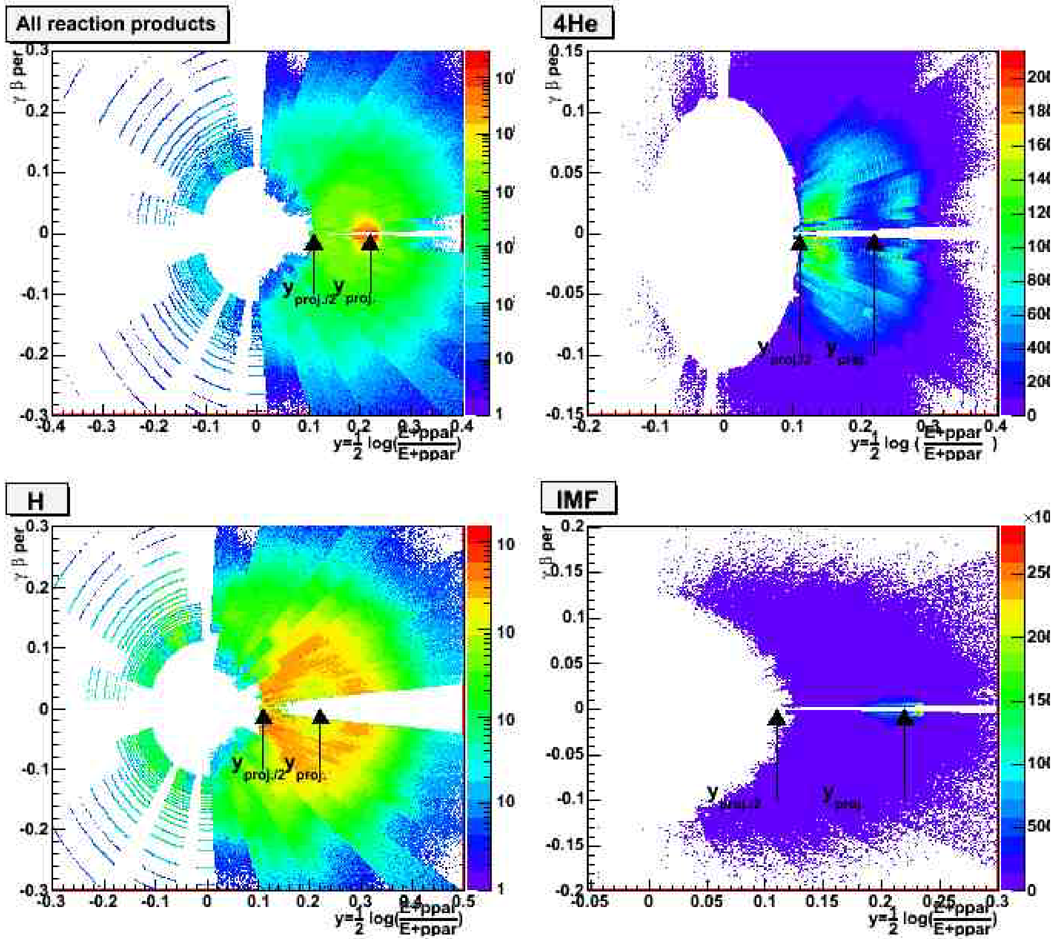
=> 816 telescopes

Particle identification



[redacted]

Selection: reaction products with velocities > $v_{proj}/2$



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:

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

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

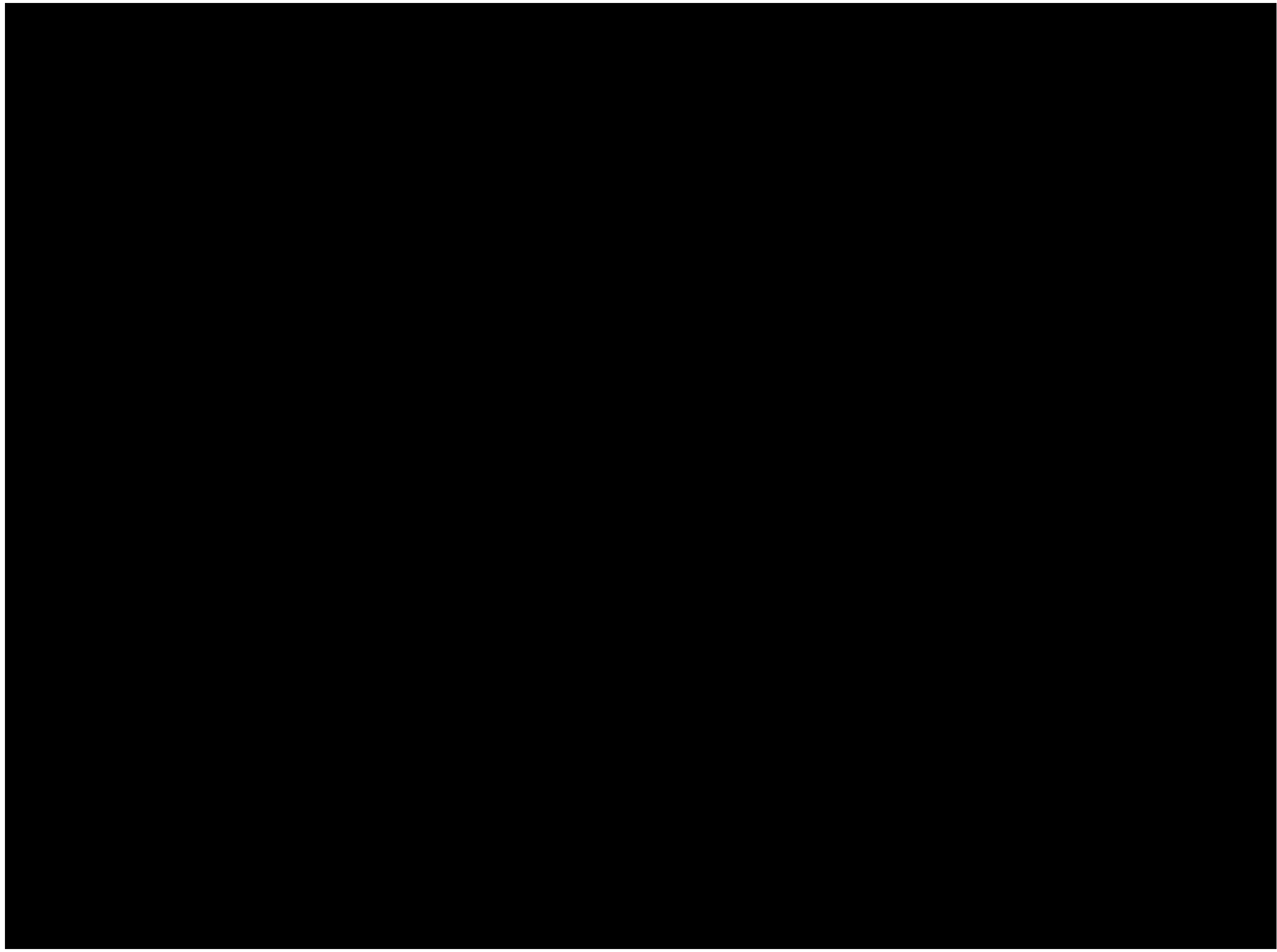
Quality of energy calibration ?
d-alpha correlations

^{6}Li

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

$E_{ex}=$ 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

3α threshold
7.275 MeV

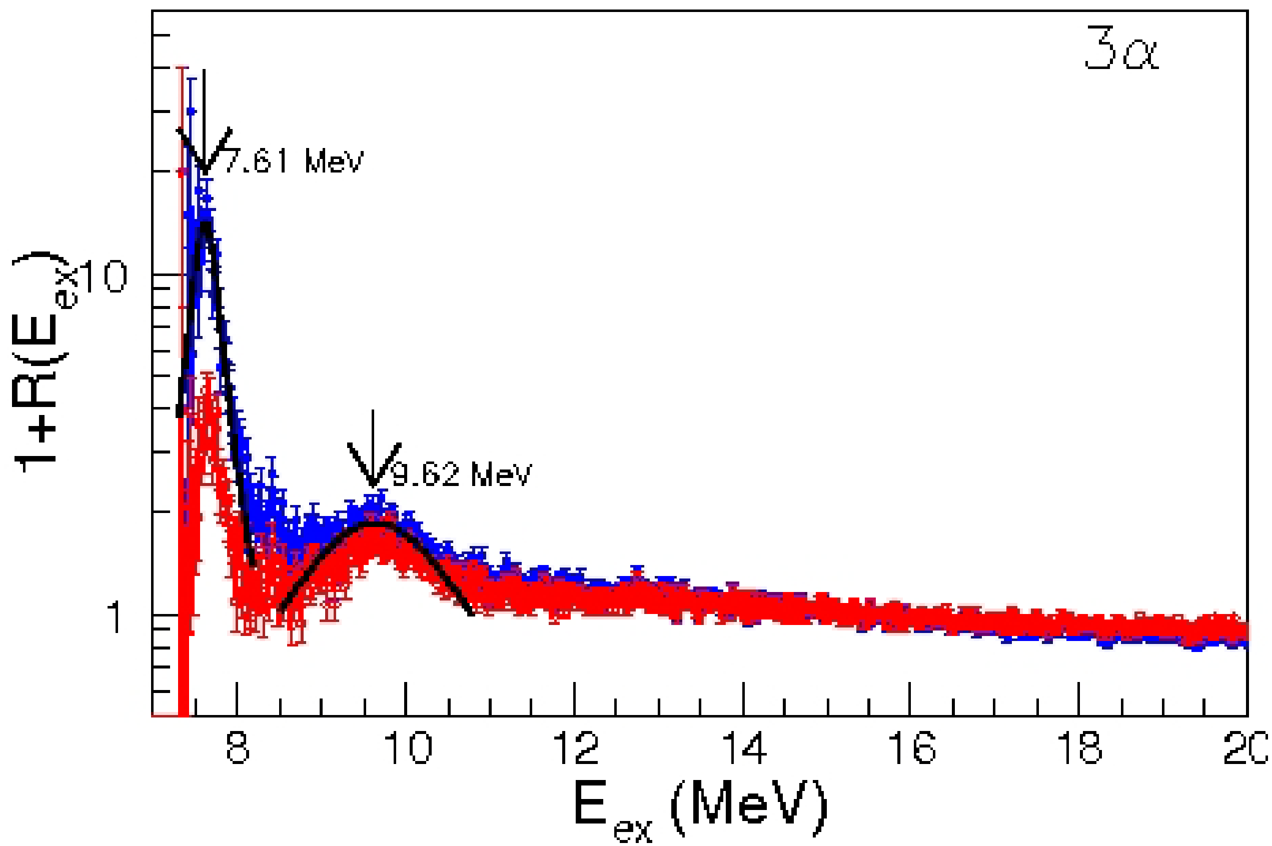
$E_{ex}=E_{tot}-Q$

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

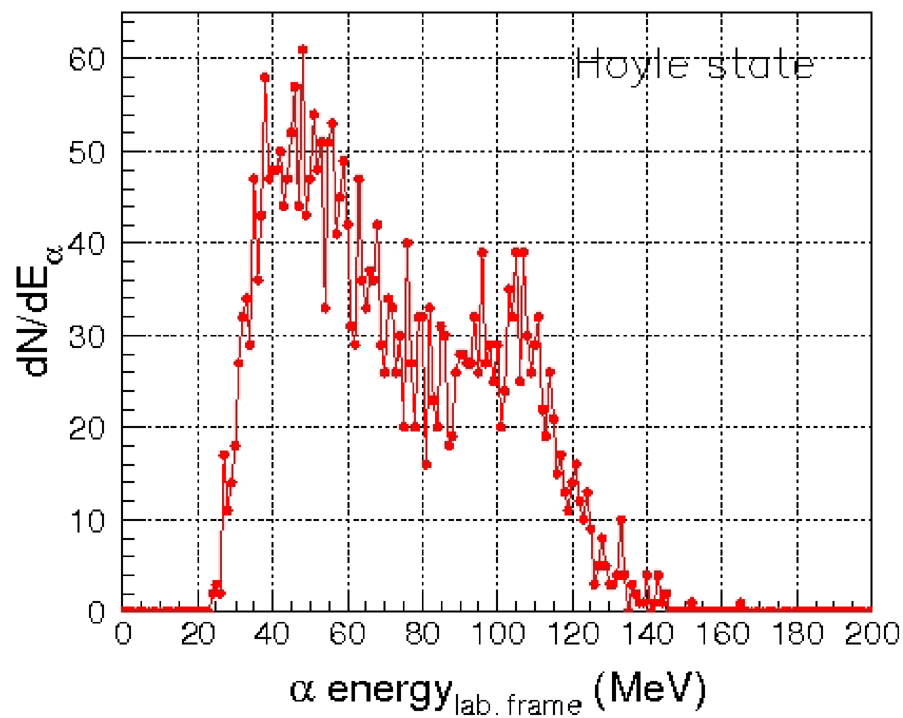
3^- 9.641 MeV (34keV)
2_2^+ 9.7 MeV (?)
0_3^+ 10.3 MeV (3MeV)

PRL soumis
arXiv:1004.3234

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:

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

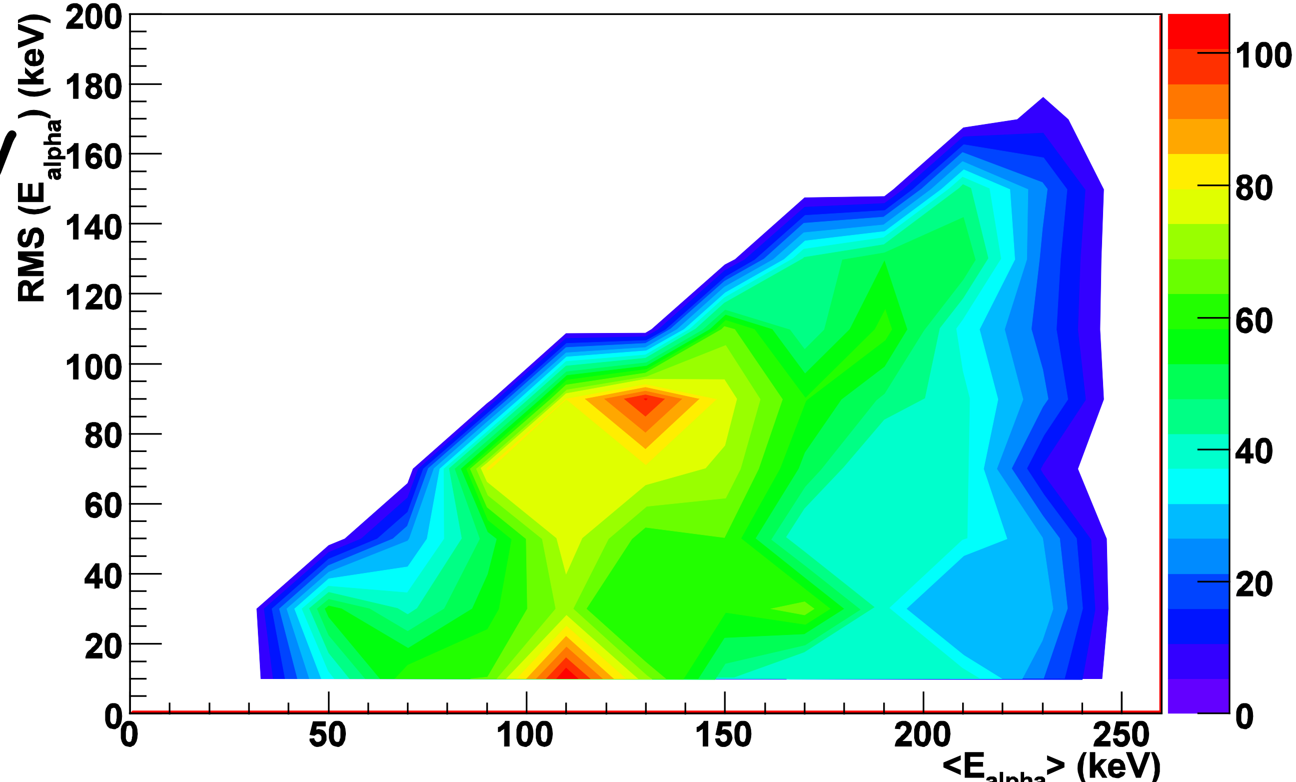
12C*-Hoyle state: alpha cond. state

Mα=3

7.37 ≤ Eex ≤ 7.97 MeV

39 events
<Eα> ≈ 110 keV
σ ≤ 25 keV

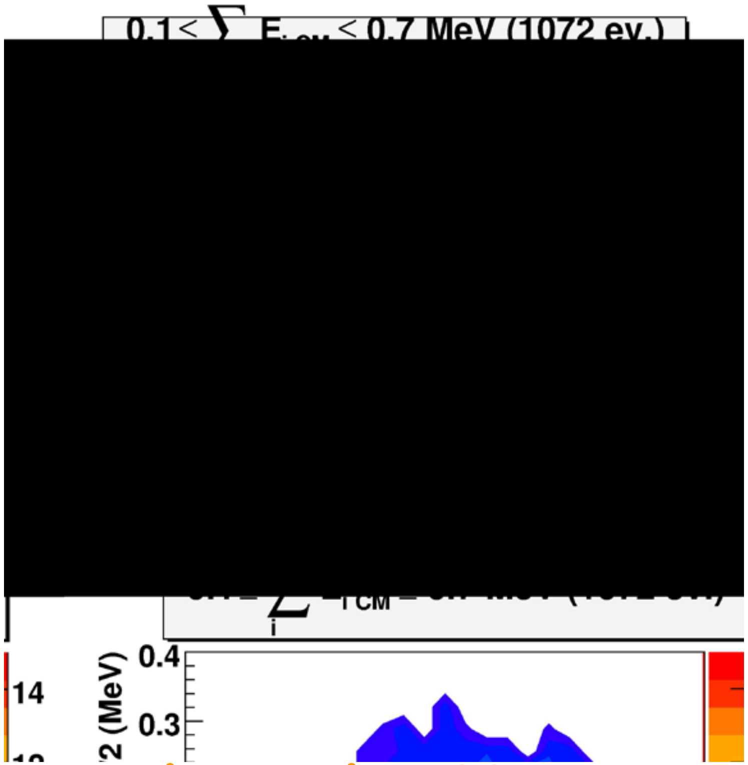
85 (241) events
<Eα> ≈ 130 keV
σ ≈ 85 keV



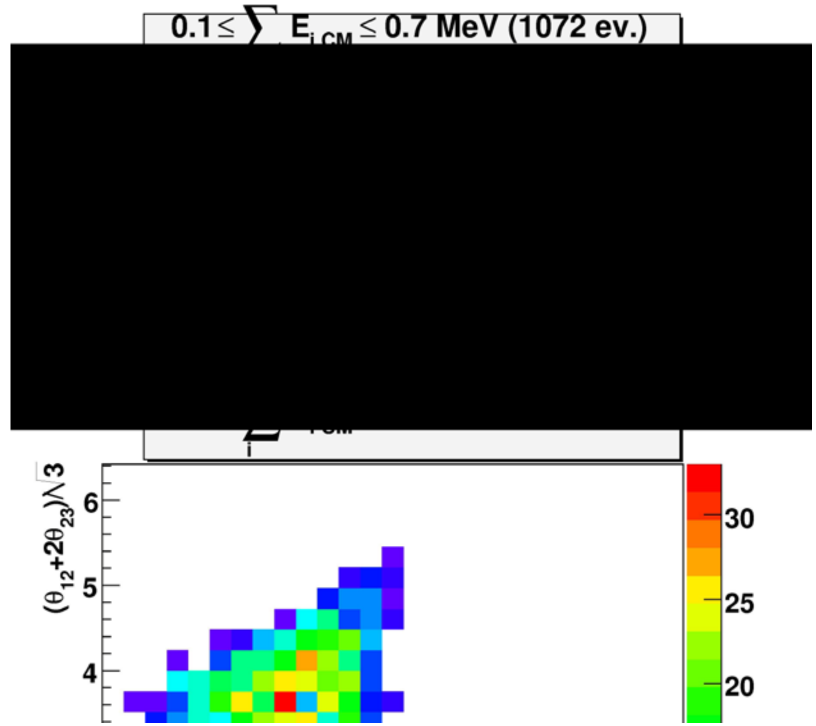
PRL soumis, arXiv:1004.3234

12C*-Hoyle state: alpha cond. state « Dalitz plots »

energy



Angle (new Dalitz)



PRL soumis, arXiv:1004.3234

three-alpha correlation function

M_α=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

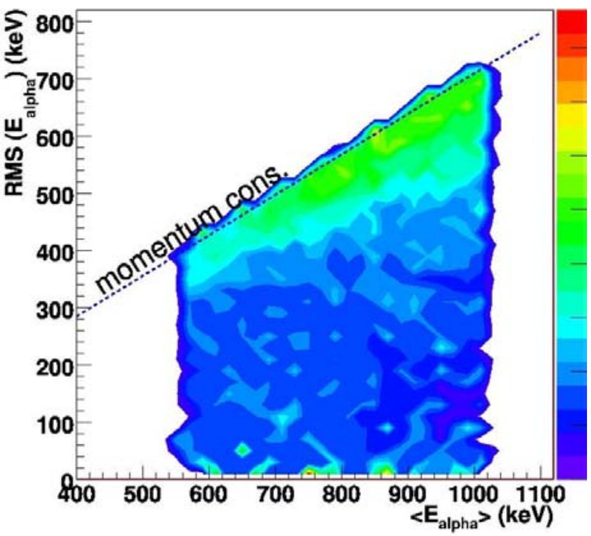
$E_{ex}=E_{tot}-Q$

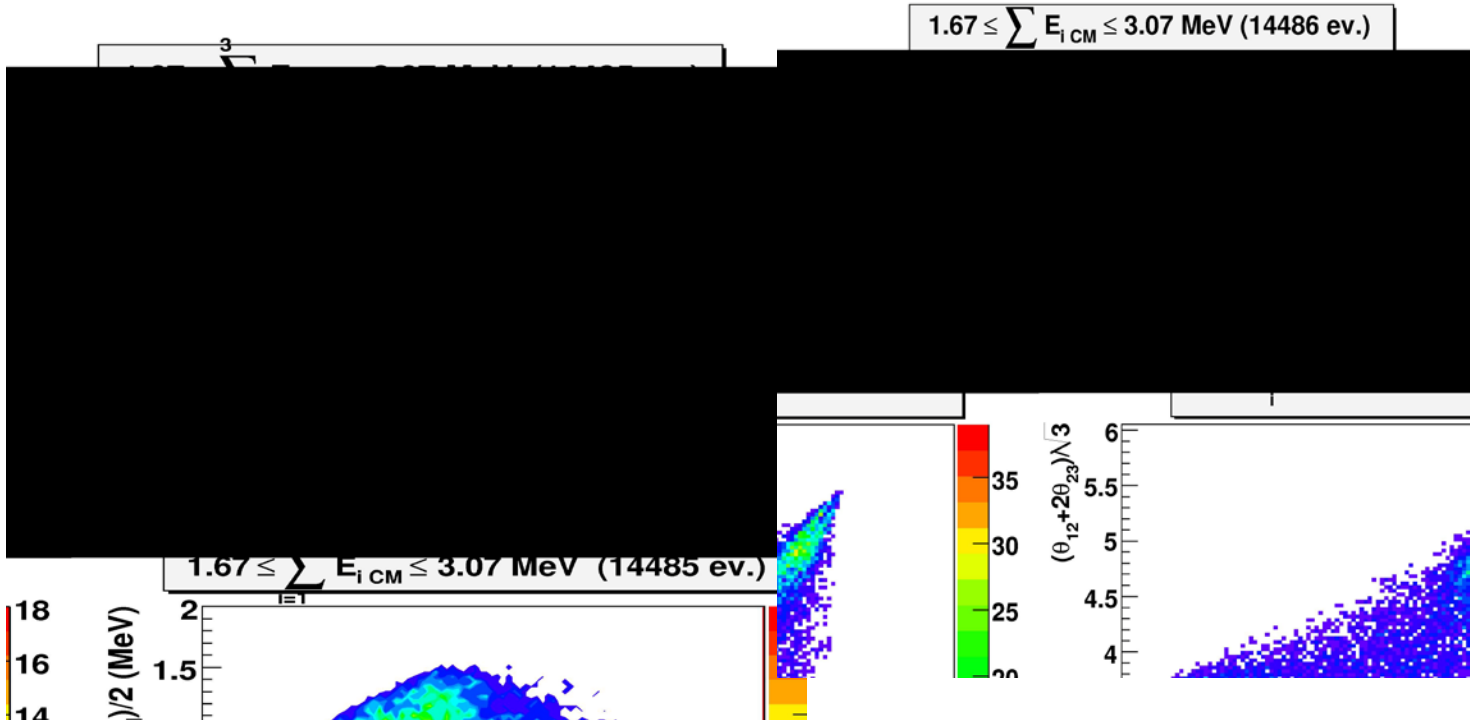
^{12}C second 0^+
7.654 MeV
Γ=8.5 eV
E_{tot}=379 keV

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

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

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





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

SOTANCP2 2010 arXiv:1009.1267

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

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

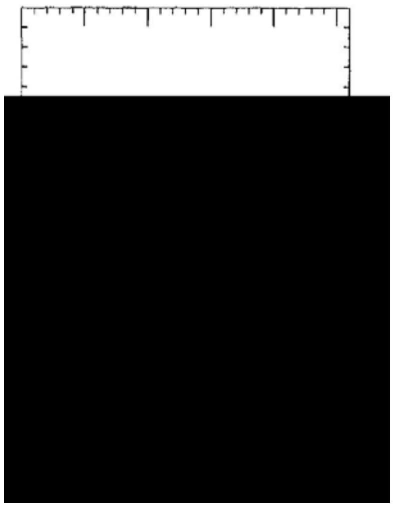
^{12}C + α threshold 14.811 MeV

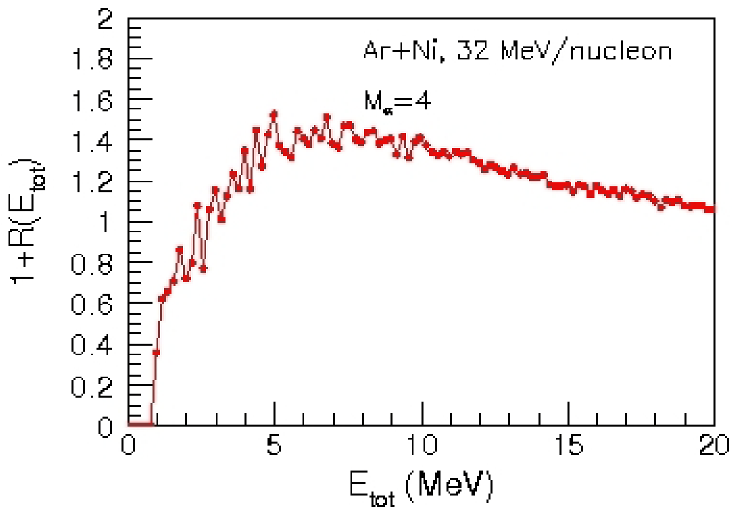
four-alpha correlation function

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

INDRA

CHIMERA





E_{ex}=E_{tot} + 14.44 MeV

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 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 => 5×10^{-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.

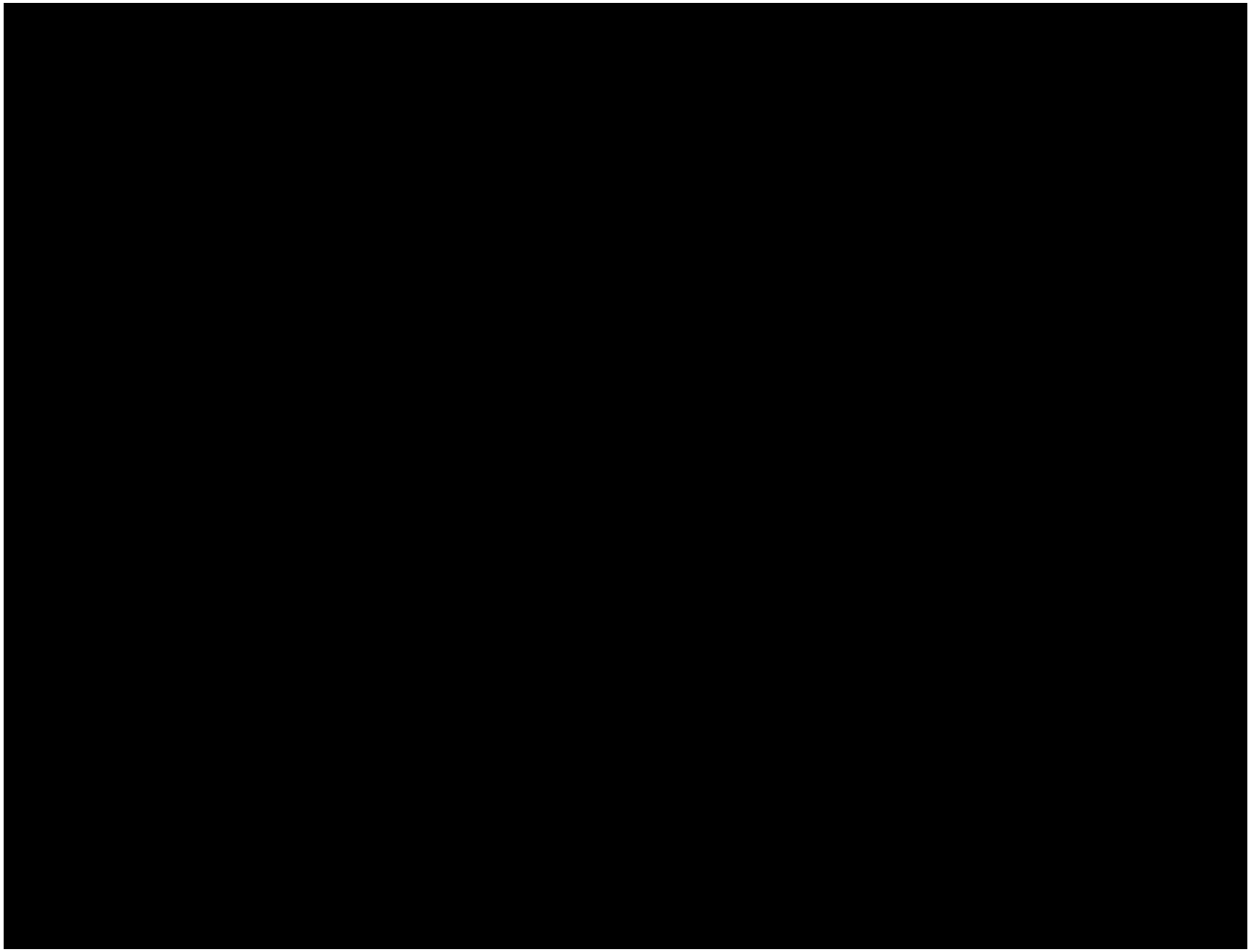
12C*-Hoyle state: BEC state

No selection (2.5 million ev.)

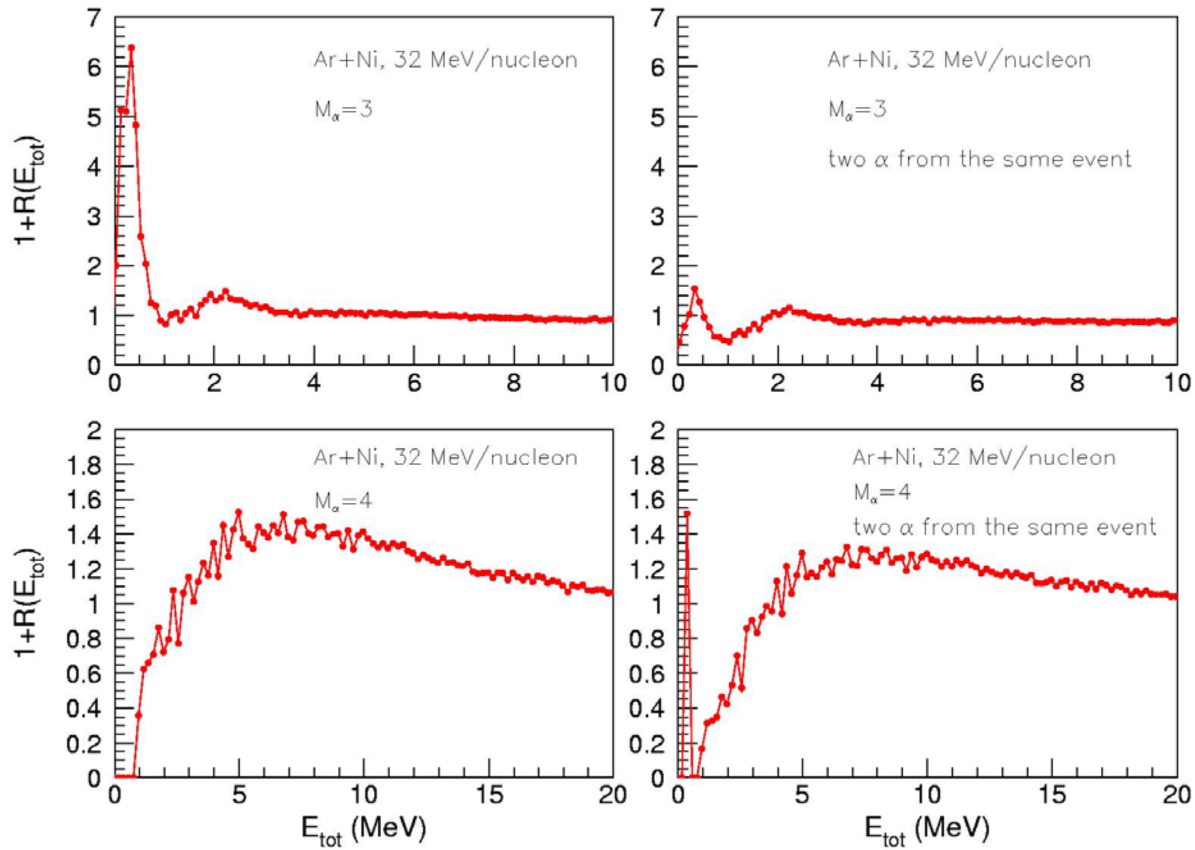
$^{12}C^*$-Hoyle state: BEC state

denominator: $\alpha+\alpha+\alpha$

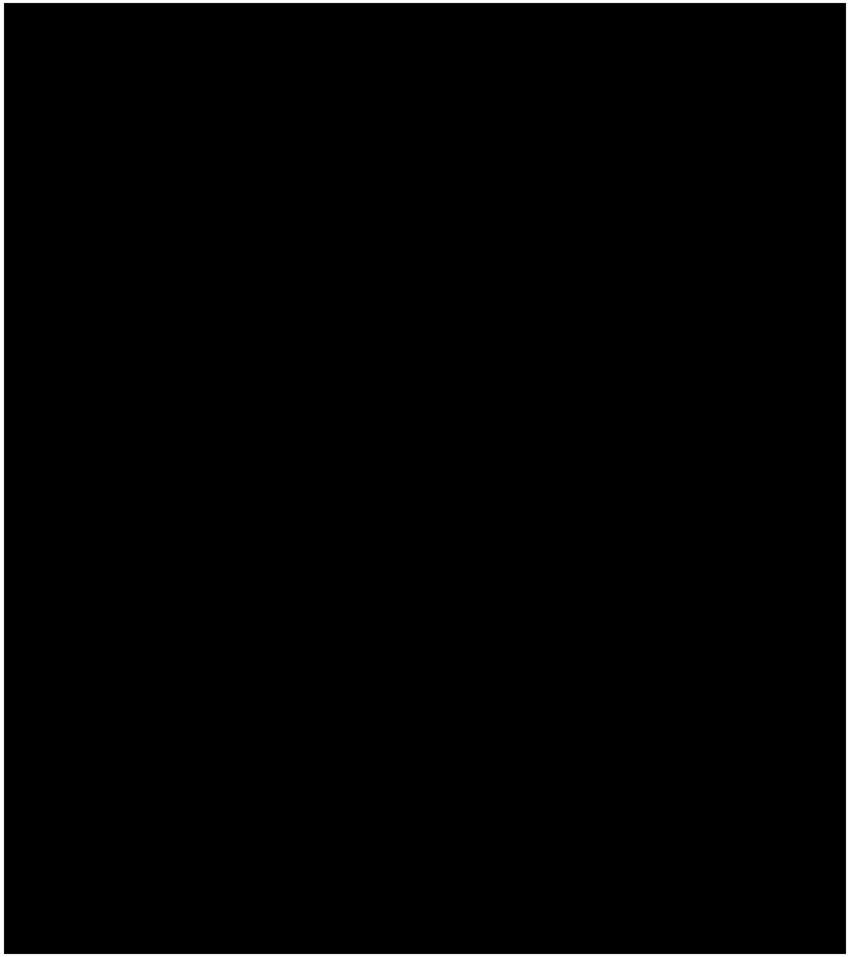
four-alpha correlation function

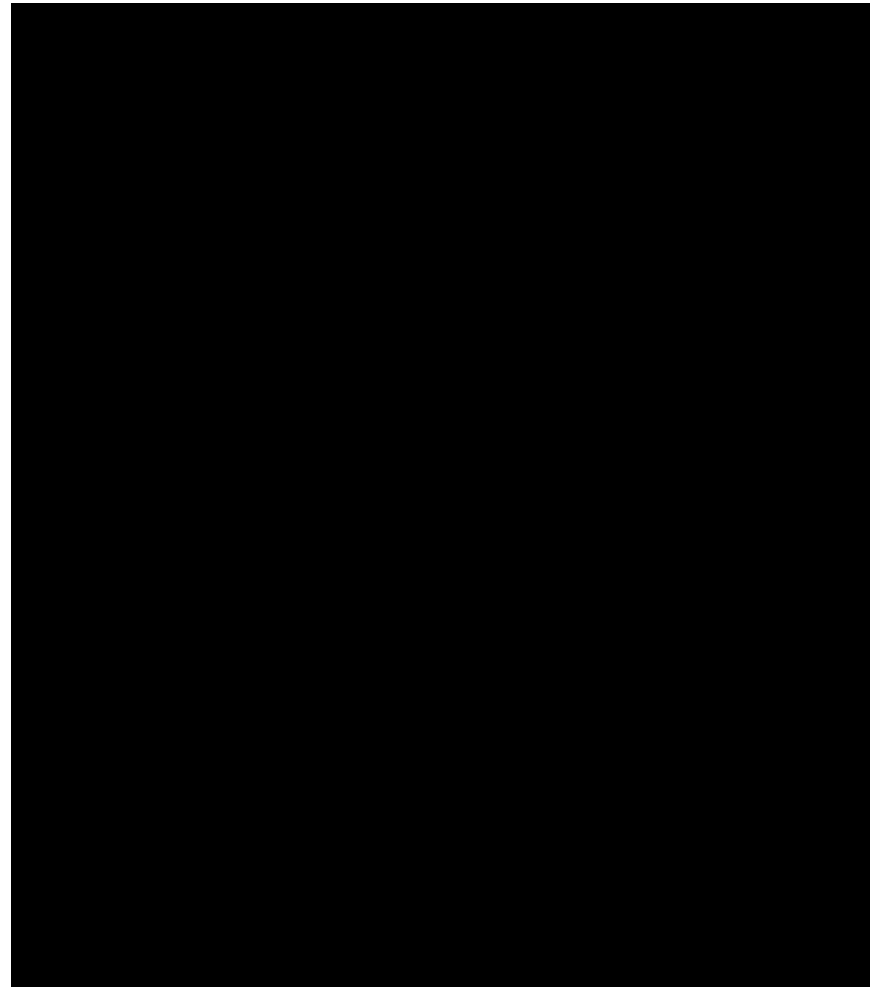


INDRA data, Ar+Ni 32 AMeV granularity too bad for 4a



3α and 3p correlation functions: numerator and denominator





CHIMERA geometry

Ring	Module	Module DP2	Telescope	PID Si	Dist. (cm)	Θ	ΔΦ	ΔΩ
1-I	16	1-16	0-15	4545-4560	350.	1.0-1.6	22.5	0.13
1-E	16	17-32	16-31	4561-4576	350.	1.6-2.6	22.5	0.21
2-I	24	1-24	32-55	4577-4600	300.	2.6-3.6	15.	0.25
2-E	24	25-48	56-79	4601-4624	300.	3.6-4.6	15.	0.33
3-I	32	1-32	80-111	4625-4656	250.	4.6-5.8	11.25	0.37
3-E	32	33-64	112-143	4657-4688	250.	5.8-7.	11.25	0.46
4-I	40	1-40	144-183	4689-4728	210.	7.-8.5	9.	0.55
4-E	40	41-80	184-223	4729-4768	210.	8.5-10.	9.	0.66
5-I	40	1-40	224-263	4769-4808	180.	10.-11.5	9.	0.77
5-E	40	41-80	264-303	4809-4848	180.	11.5-13.	9.	0.87
6-I	48	1-48	304-351	4849-4896	160.	13.-14.5	7.5	0.81

[redacted]

	0.90	6-E	48	49-96	352-399	4897-4944	160.	14.5-16.	7.5
	1.34	7-I	48	1-48	400-447	4945-4992	140.	16.-18.	7.5
	1.49	7-E	48	49-96	448-495	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	100.	24.-27.	7.5
	3.27	9-E	48	49-96	640-687	5185-5232	100.	27.-30.	7.5
5		10	32	32	688-719	-	40.	30.-38.	11.2
5		11	32	32	720-751	-	40.	38.-46.	11.2
5		12	32	32	752-783	-	40.	46.-54.	11.2
5		13	32	32	784-815	-	40.	54.-62.	11.2
5		14	32	32	816-847	-	40.	62.-70.	11.2
5		15	32	32	848-879	-	40.	70.-78.	11.2
5		16	32	32	880-911	-	40.	78.-86.	11.2
5		17	32	32	912-943	-	40.	86.-94.	11.2