α particle correlations for studying Nuclear Structure and Dynamics

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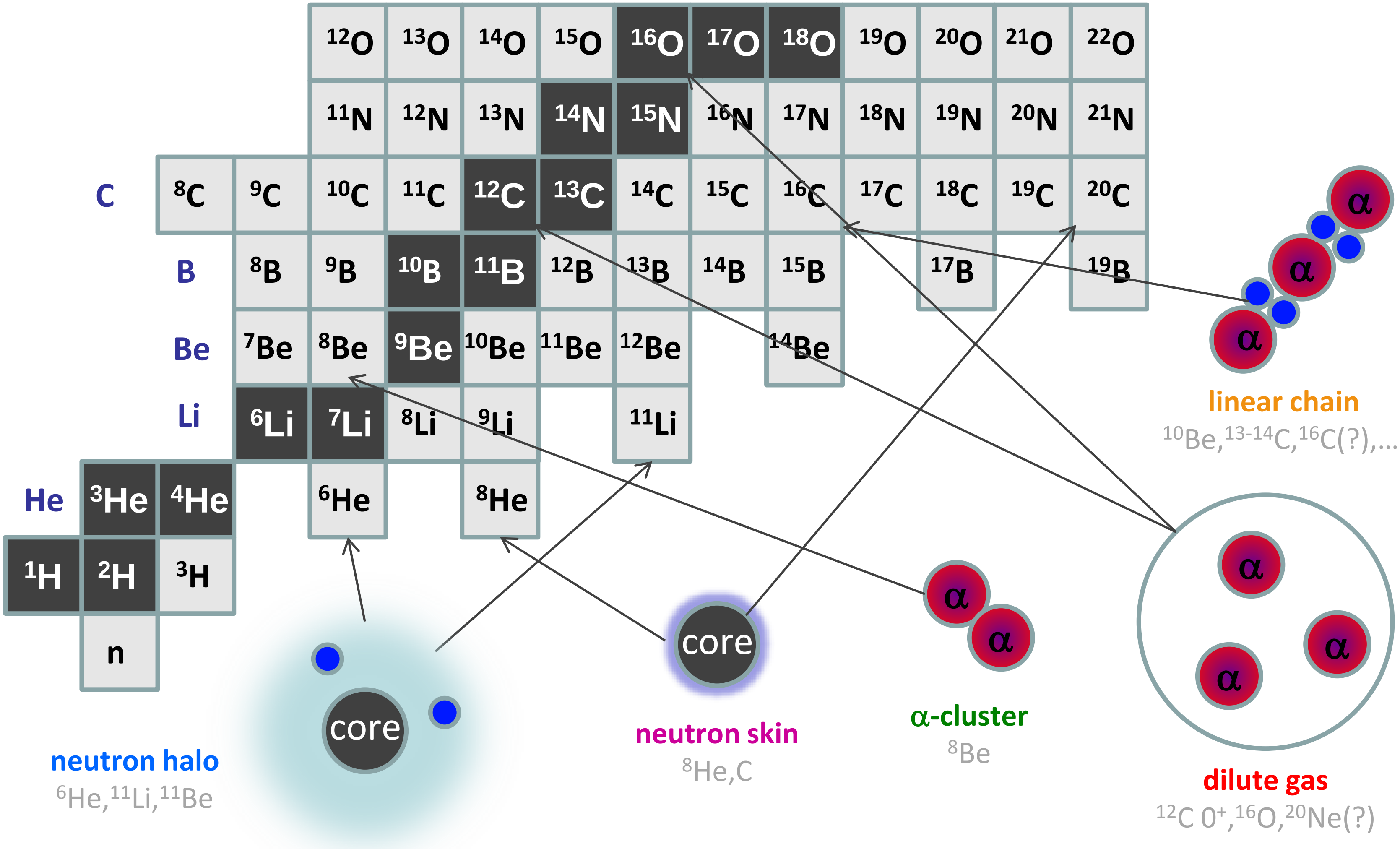
Exotic structures in light nuclei

Complexity of nuclear force → deviation from the ***sphericity***: axial deformation (collective behaviours), spatial re-organization of nucleons in bounded **sub-units** (***cluster model***).



				^{12}O	^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O	^{21}O	^{22}O
				^{11}N	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	^{18}N	^{19}N	^{20}N	^{21}N
	C	^{8}C	^{9}C	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C	^{17}C	^{18}C	^{19}C	^{20}C
		B	^{8}B	^{9}B	^{10}B	^{11}B	^{12}B	^{13}B	^{14}B	^{15}B		^{17}B		^{19}B
		Be	^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be		^{14}Be				
		Li	^{6}Li	^{7}Li	^{8}Li	^{9}Li		^{11}Li						
He	^{3}He	^{4}He		^{6}He		^{8}He								
^{1}H	^{2}H	^{3}H												
	n													

linear chain
^{10}Be, $^{13\text{-}14}$C, ^{16}C(?),…

neutron halo
^{6}He, ^{11}Li, ^{11}Be

neutron skin
^{8}He, C

α-cluster
^{8}Be

dilute gas
^{12}C 0^+, ^{16}O, ^{20}Ne(?)

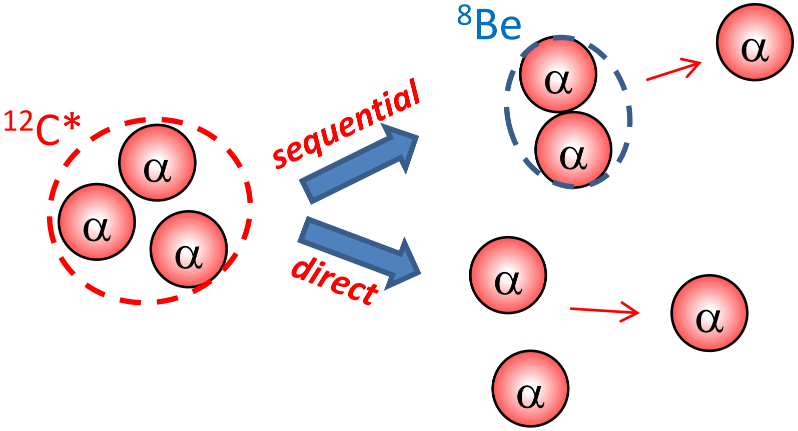
Outline of the talk:

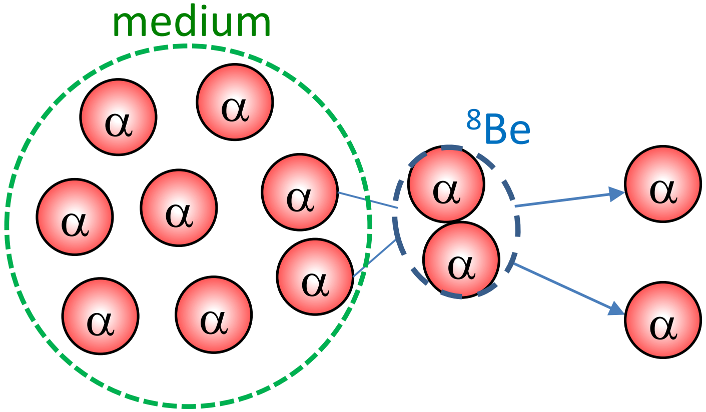
1. A *high-precision* α-particle correlation experiment

   the direct decay branch of the Hoyle state in ^{12}C

2. An *in-medium* α-α correlation study

   analysis of the systematic $^{36}Ar + ^{58}Ni$ from 32 AMeV to 95 AMeV





3α correlations and the Hoyle state in ^{12}C

3α correlations and the Hoyle state in ^{12}C

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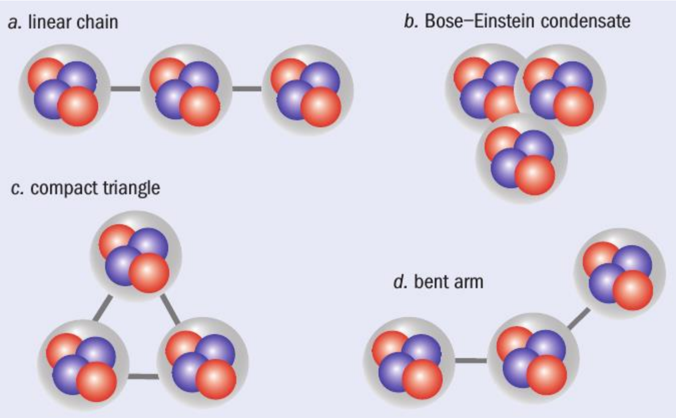
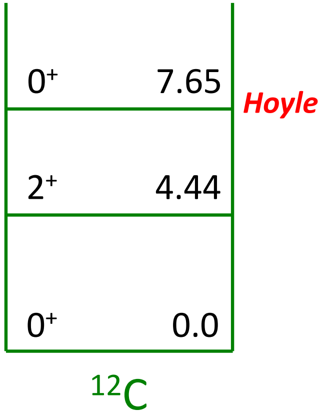
In Nuclear Structure

Cluster state of ^{12}C located at 7.654 MeV (0^+) → quite unusual and not well understood properties → challenging question in nuclear physics.



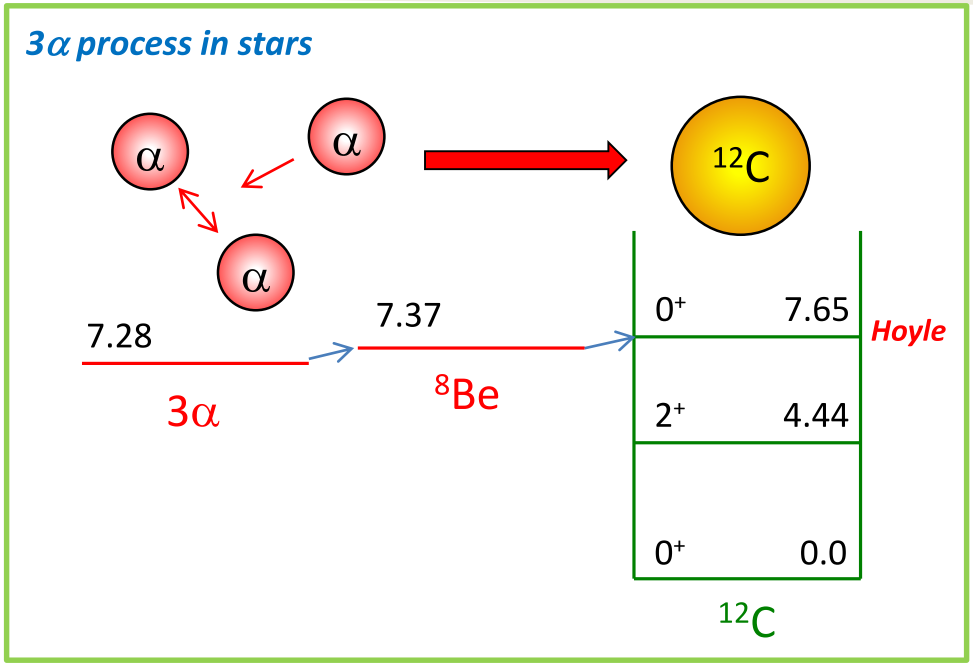
D. Jenkins and O. Kirsebom, The Secret of Life, Physics World Feb. 2013

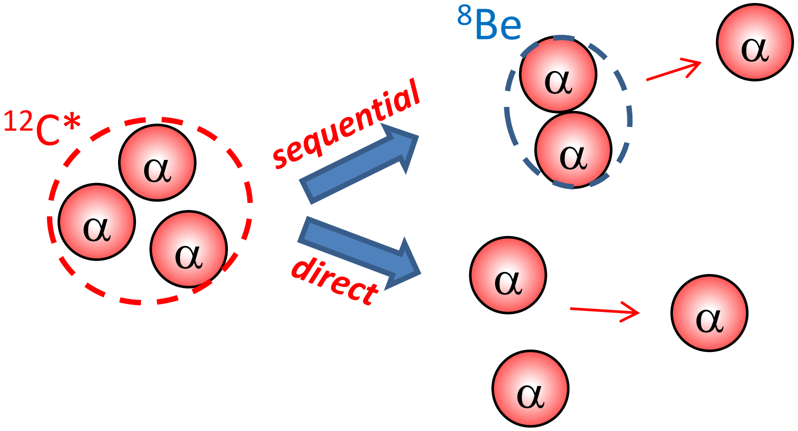


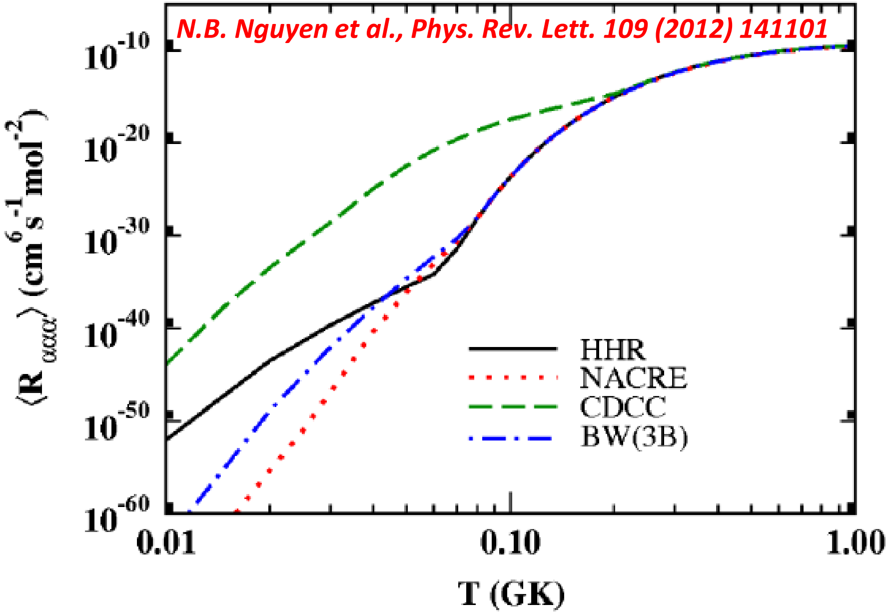
3α correlations and the Hoyle state in ^{12}C

In Nuclear Astrophysics

Proposed by Fred Hoyle in 1953 → explaination to the *3α process* in stars (helium burning) → production of carbon and heavier elements in the universe. At low temperatures ($T<10^8$ K) → *non-resonant processes dominate* → need to know the $\Gamma_{3\alpha}$!


3α process in stars



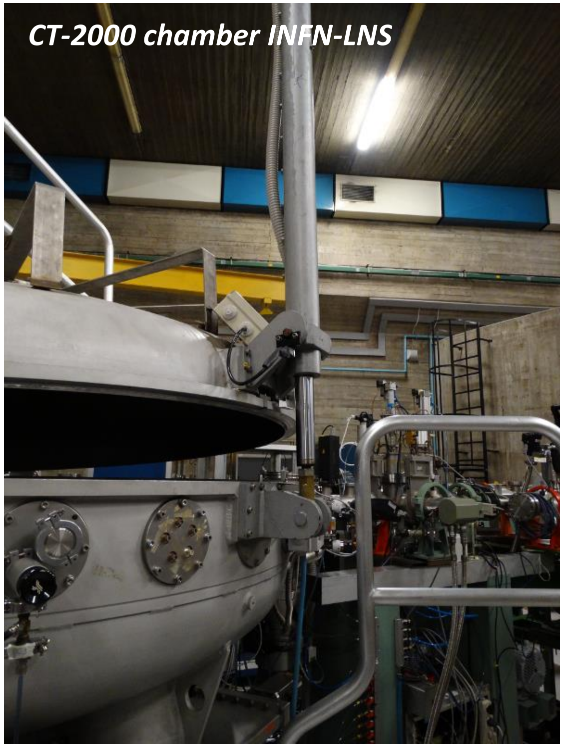

N.B. Nguyen et al., Phys. Rev. Lett. 109 (2012) 141101

3α correlations and the Hoyle state in ^{12}C

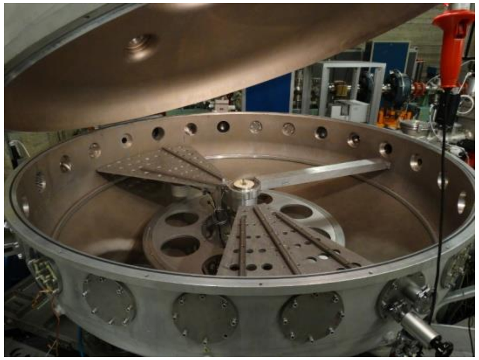
The ***HOYLE*** (***H***odoscope ***O***riented ***Y***ield ***L***oader ***E***xperiment) experiment at INFN-LNS → a new *high statistics* and *low background* investigation of the HOYLE state by means of the $^{14}N(d,\alpha_2)^{12}C(7.654)$ reaction.

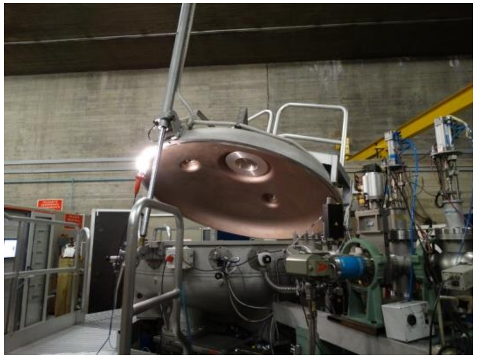

Tandem 15MV

Istituto Nazionale di Fisica Nucleare
LNS - Laboratori Nazionali del Sud

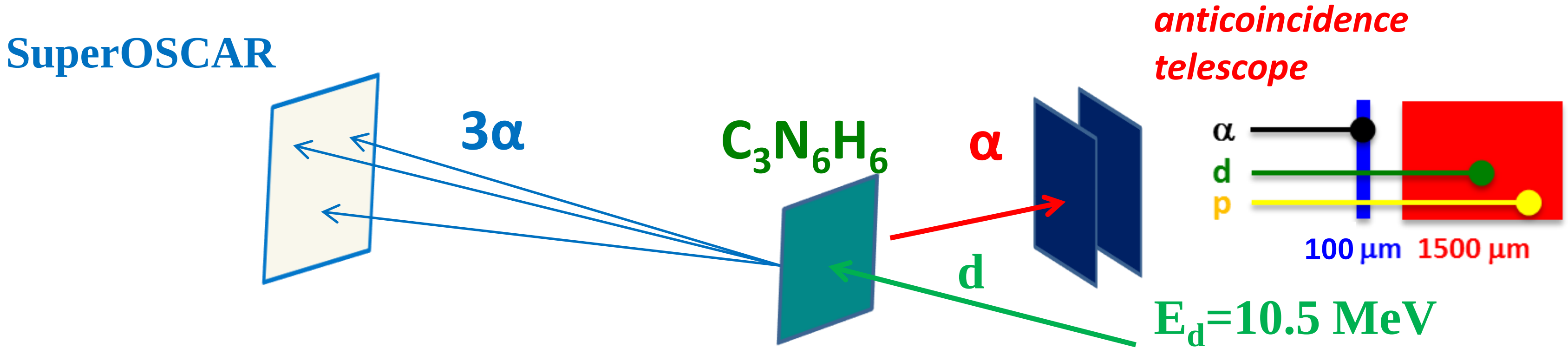

CT-2000 chamber INFN-LNS

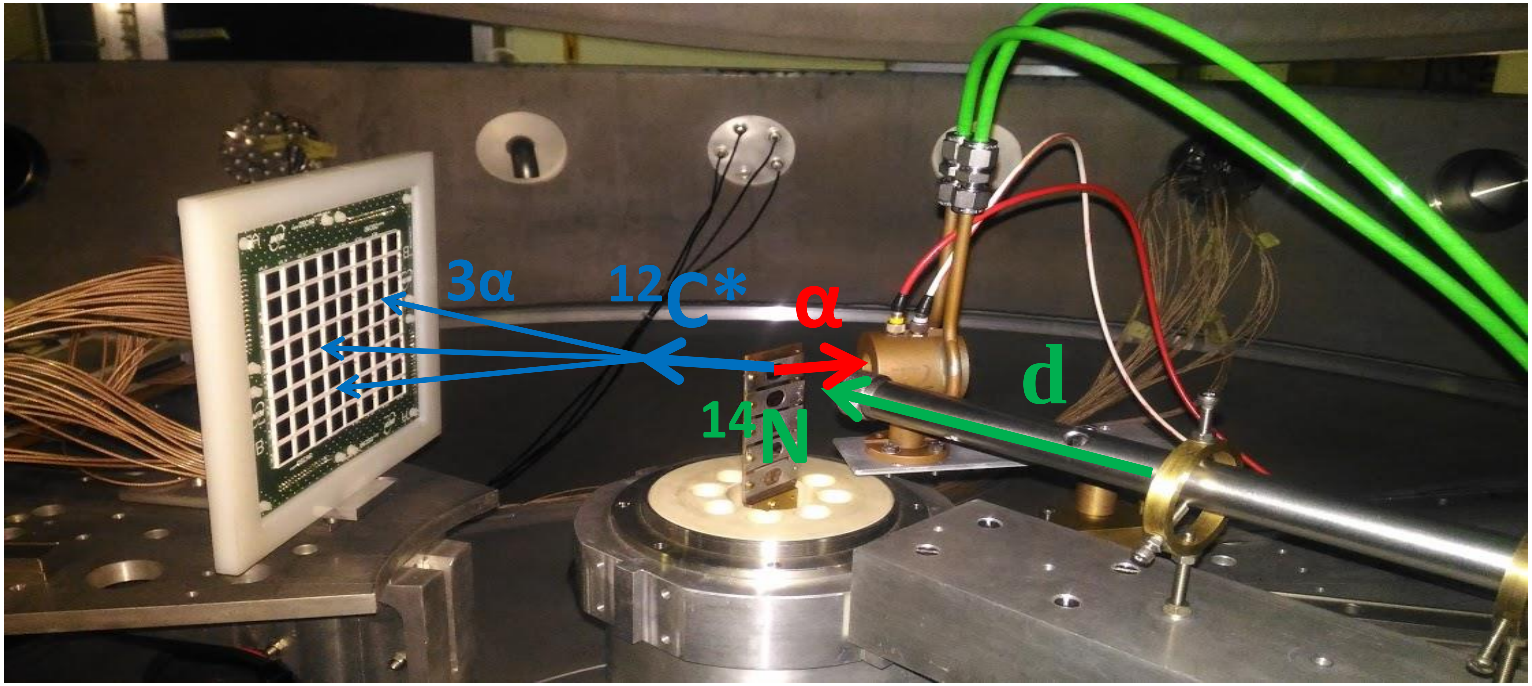
- *d beam* at E_d = 10.5 MeV;
- $C_3N_6H_6$ target (**40 μg/cm²**) + **5/10 μg/cm²** *backing* C;
- $I_d \approx 4enA$;
- $\approx 30\ days$ of beam time;
- $\theta_{lab} = 125°$ anti-telescope + ***superOSCAR*** hodoscope (31.4°).



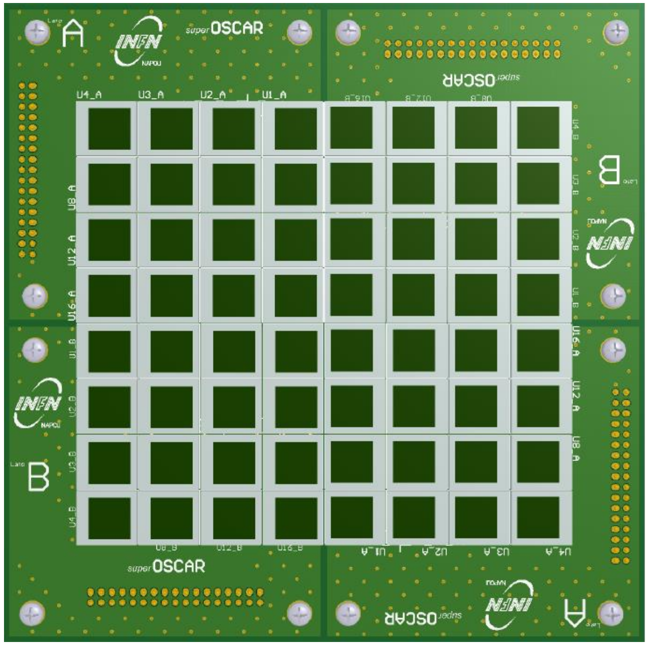


Basic *idea* and experimental *layout*

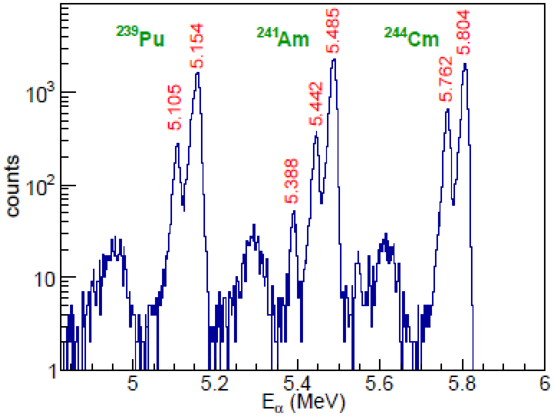




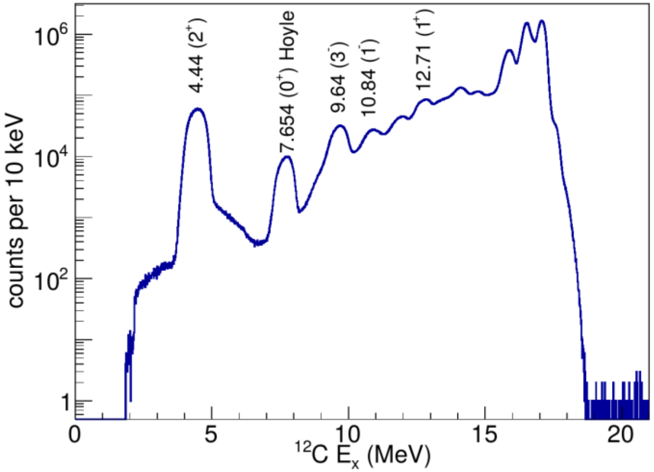
The superOSCAR hodoscope



- 64 Hamamatsu S-3590 300μm silicon pads (1cmx1cm active area);
- $\approx 0.125\ cm$ ceramic frame;
- 4 modules 4x4 pads in 2x2 configuration;
- 4 pre-amplifiers Net Instruments NPA-16FE (16 chs);

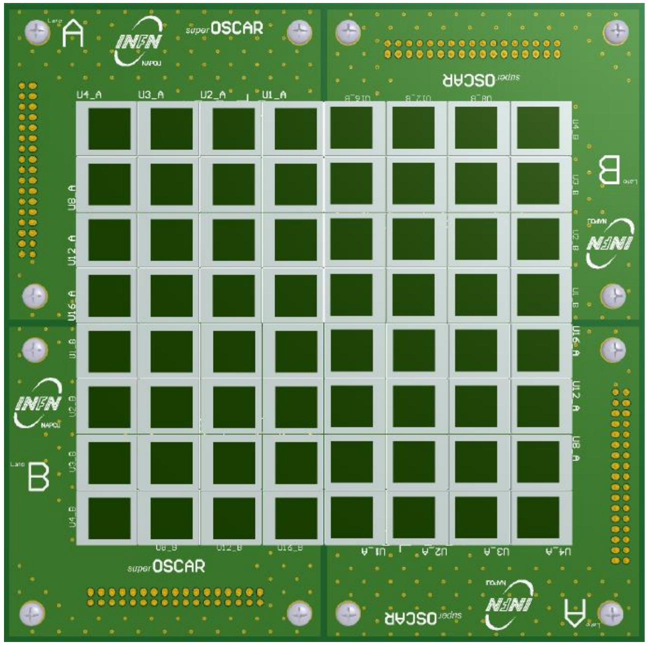


3a source →
0.2% energy resolution.



single-particle energy spectrum in the anti-telescope

The superOSCAR hodoscope



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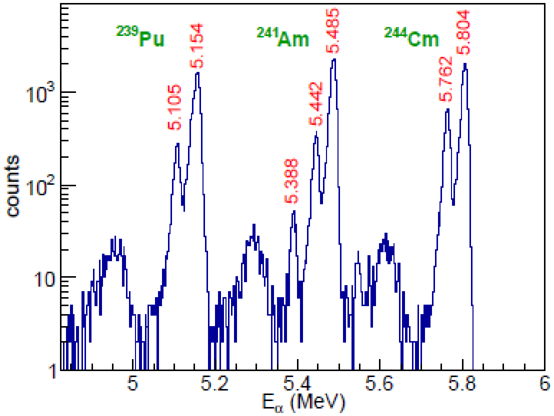

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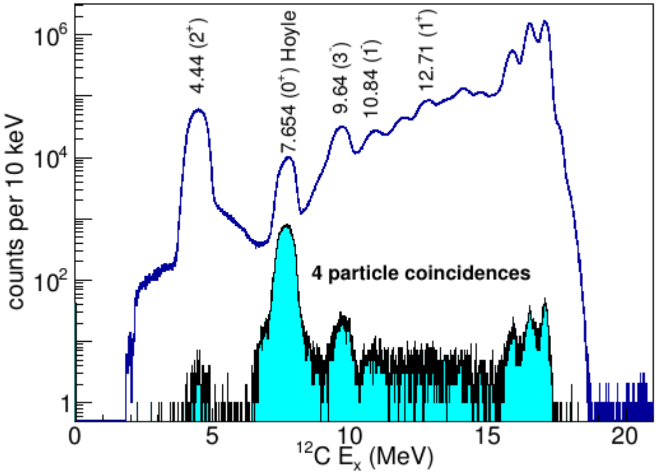


single-particle energy spectrum in the anti-telescope

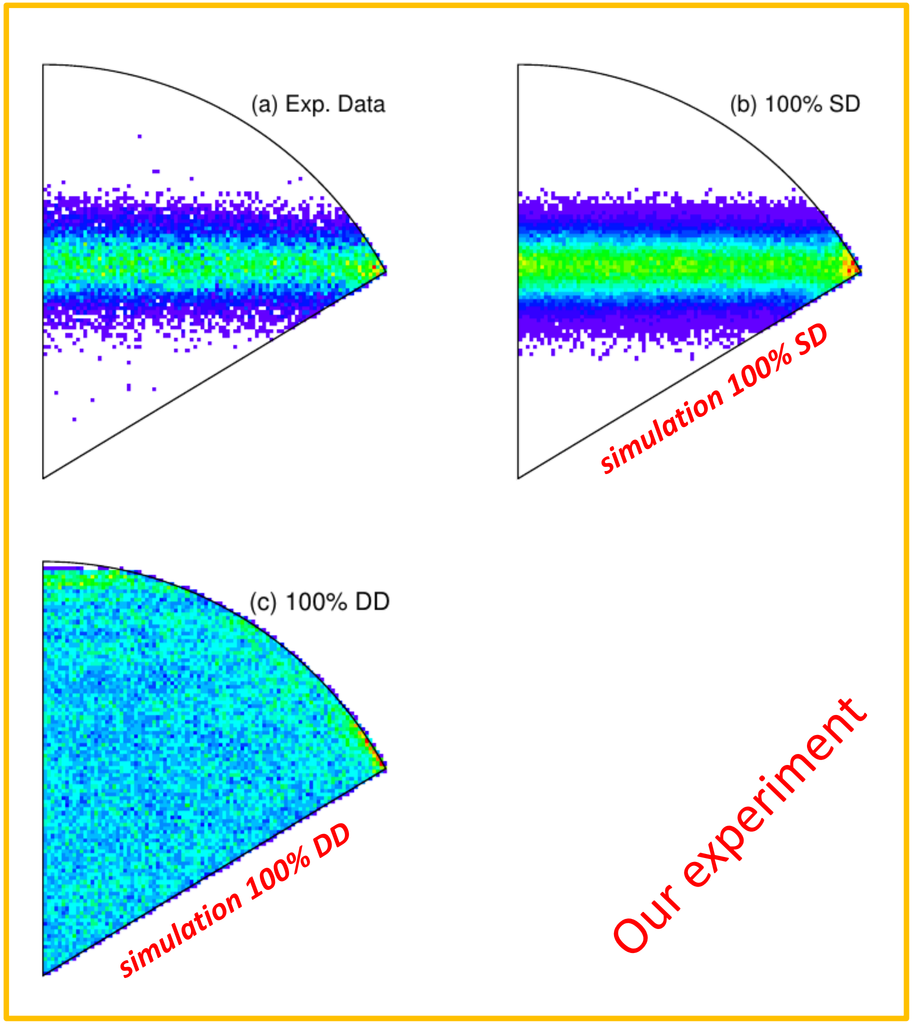
single-particle energy spectrum (4-particles fully-reconstructed events → superOSCAR)

Study of sequential vs direct mechanism: Symmetric Dalitz Plot

$$\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$$

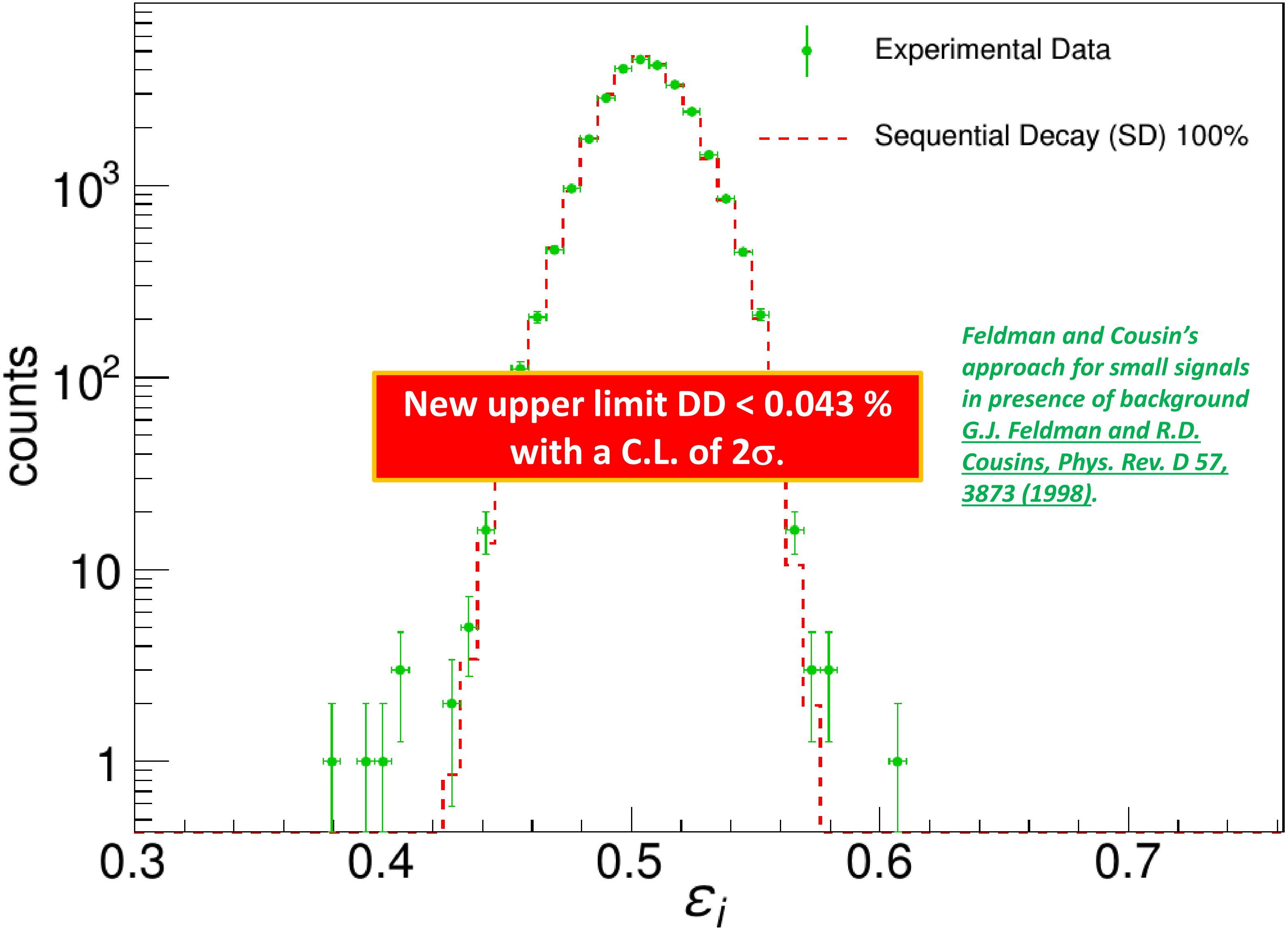
$$\varepsilon_i > \varepsilon_j > \varepsilon_k$$

$$\boldsymbol{x = \sqrt{3}(\varepsilon_j - \varepsilon_k)}$$
$$\boldsymbol{y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k}$$



28000 counts under the sequential decay peak
→ compatible with ***fully sequential process!***

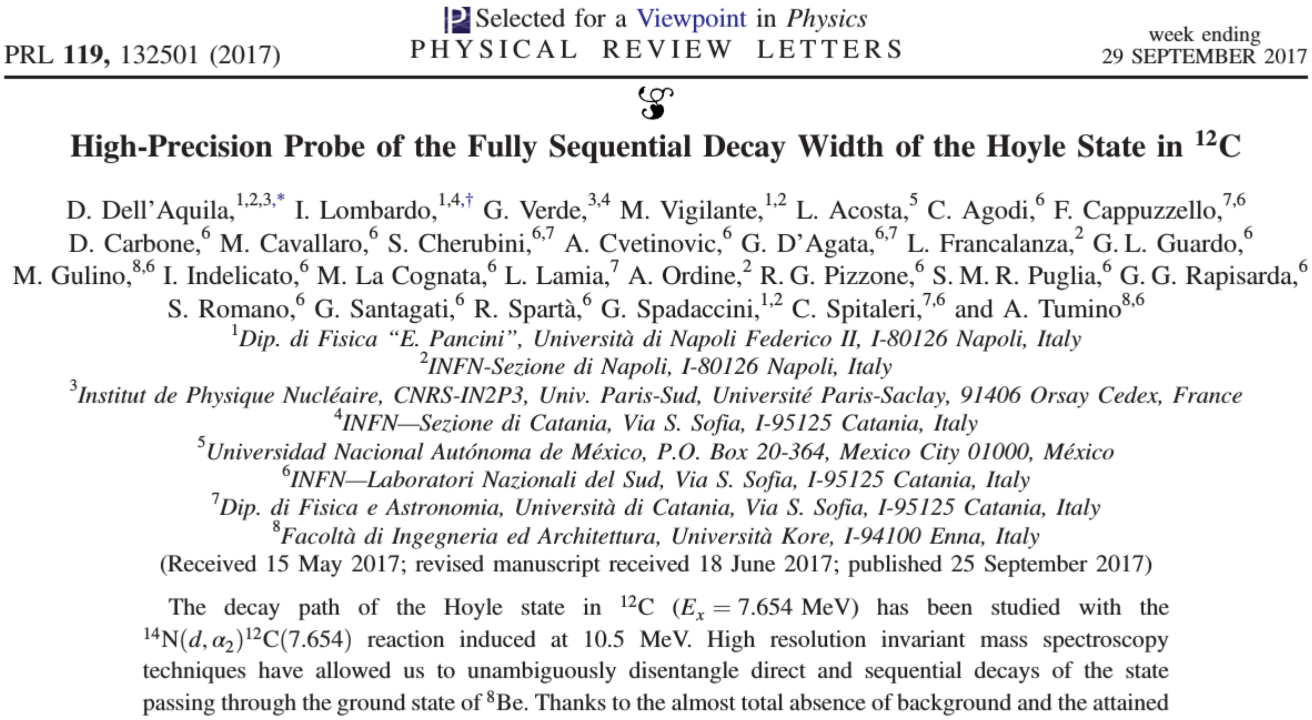
Study of sequential vs direct mechanism: Symmetric Dalitz Plot



New upper limit DD < 0.043 % with a C.L. of 2σ.

Feldman and Cousin's approach for small signals in presence of background *G.J. Feldman and R.D. Cousins, Phys. Rev. D 57, 3873 (1998).*

3α correlations and the Hoyle state in ^{12}C



Selected for a Viewpoint in *Physics*
PRL **119,** 132501 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

High-Precision Probe of the Fully Sequential Decay Width of the Hoyle State in ^{12}C

D. Dell'Aquila,[1,2,3,*] I. Lombardo,[1,4,†] G. Verde,[3,4] M. Vigilante,[1,2] L. Acosta,[5] C. Agodi,[6] F. Cappuzzello,[7,6]
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M. Gulino,[8,6] I. Indelicato,[6] M. La Cognata,[6] L. Lamia,[7] A. Ordine,[2] R. G. Pizzone,[6] S. M. R. Puglia,[6] G. G. Rapisarda,[6]
S. Romano,[6] G. Santagati,[6] R. Spartà,[6] G. Spadaccini,[1,2] C. Spitaleri,[7,6] and A. Tumino[8,6]
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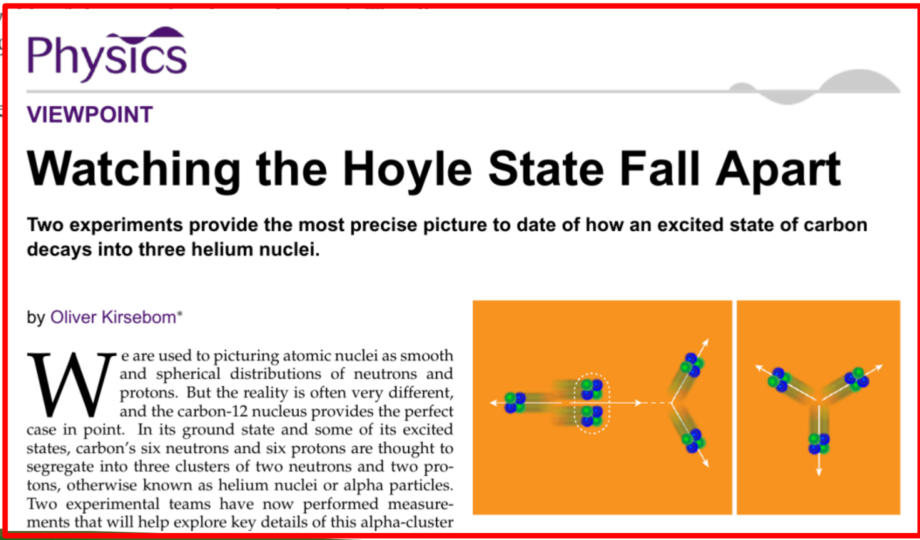
(Received 15 May 2017; revised manuscript received 18 June 2017; published 25 September 2017)

The decay path of the Hoyle state in ^{12}C ($E_x = 7.654$ MeV) has been studied with the ^{14}N$(d,\alpha_2)^{12}$C(7.654) reaction induced at 10.5 MeV. High resolution invariant mass spectroscopy techniques have allowed us to unambiguously disentangle direct and sequential decays of the state passing through the ground state of ^{8}Be. Thanks to the almost total absence of background and the attained resolution, a fully sequential decay contribution to the w
decay width is negligible, with an upper limit of 0.043% (
factor 5 higher than previous studies. This has significant
constraints to 3α cluster model calculations, where highe

DOI: 10.1103/PhysRevLett.119.132501



Physics

VIEWPOINT

Watching the Hoyle State Fall Apart

Two experiments provide the most precise picture to date of how an excited state of carbon decays into three helium nuclei.

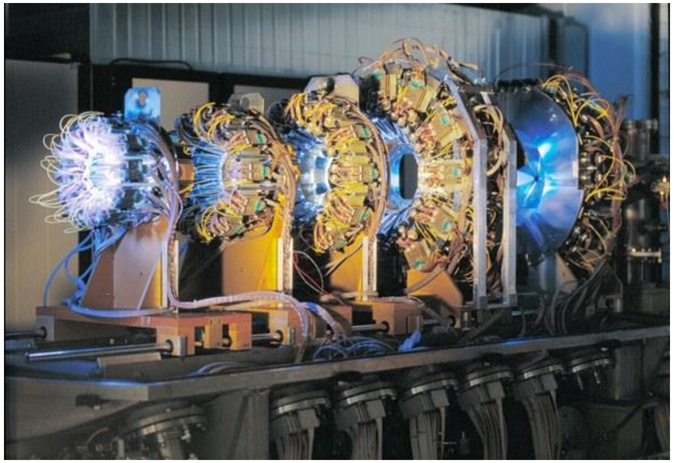
by Oliver Kirsebom*

We are used to picturing atomic nuclei as smooth and spherical distributions of neutrons and protons. But the reality is often very different, and the carbon-12 nucleus provides the perfect case in point. In its ground state and some of its excited states, carbon's six neutrons and six protons are thought to segregate into three clusters of two neutrons and two protons, otherwise known as helium nuclei or alpha particles. Two experimental teams have now performed measurements that will help explore key details of this alpha-cluster

***ViewPoint* in Physics →**

2α correlations in Heavy Ion Collisions, in-medium studies.

Second example: 2α correlations in HICs



INDRA *4π multi-detector*

angular coverage ≈ 90% (4π)
336 *independent cells*
telecopes C_3F_8 gas chamber – Si (300 μm) – CsI (5-14cm)

ADVANTAGES

- fully angular coverage → input parameters for the construction of simulations;
- good characterization of events.

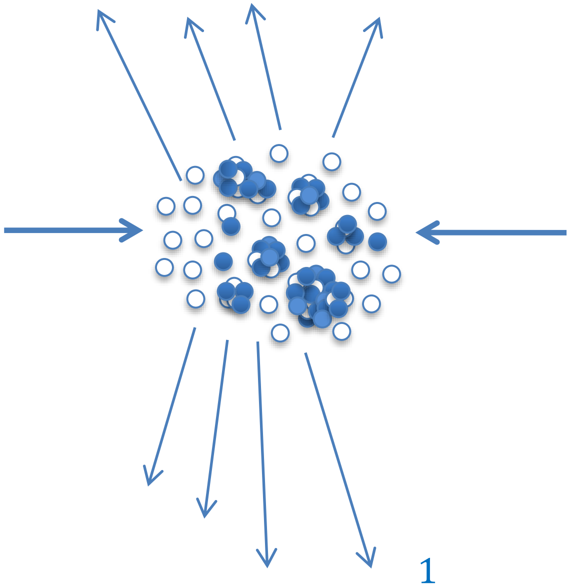
DISADVANTAGES

- limited angular resolution;
- not complete isotopic identification (Z<=4).

Second example: 2α correlations in HICs

^{36}Ar+^{58}Ni collisions at 74 AMeV with INDRA: α-α correlations

Selection of central events → transverse energy method



$$E_{t12_i} = \frac{1}{2} m_i (v_i \ \sin(\theta))^2$$

$$E_{t12} = \sum_{Z=1,2} E_{t12_i}$$

Cavata method

$$\tilde{b} = \sqrt{\frac{1}{N} \int_{E_{t12}^{max}}^{E_{t12}^{\star}} Y(E_{t12}) dE_{t12}}$$

$E_{t12} > 221 MeV$ → *Central collision* events ($\tilde{b} \leq 0.3$)

from L. Francalanza et al.

Colliding system	$E^{\star}_{t12}$ (MeV)
^{36}Ar + ^{58}Ni 32 AMeV	183
^{36}Ar + ^{58}Ni 40 AMeV	221
^{36}Ar + ^{58}Ni 52 AMeV	285
^{36}Ar + ^{58}Ni 63 AMeV	352
^{36}Ar + ^{58}Ni 74 AMeV	421
^{36}Ar + ^{58}Ni 84 AMeV	479
^{36}Ar + ^{58}Ni 95 AMeV	550

2α correlations in HICs → in-medium studies

$$\sum Y_{1,2}(\vec{p}_1,\vec{p}_2) = \boxed{Y_N(q_{rel})} + \boxed{Y_{unco}(q_{rel})} + \boxed{Y_C(q_{rel})}$$

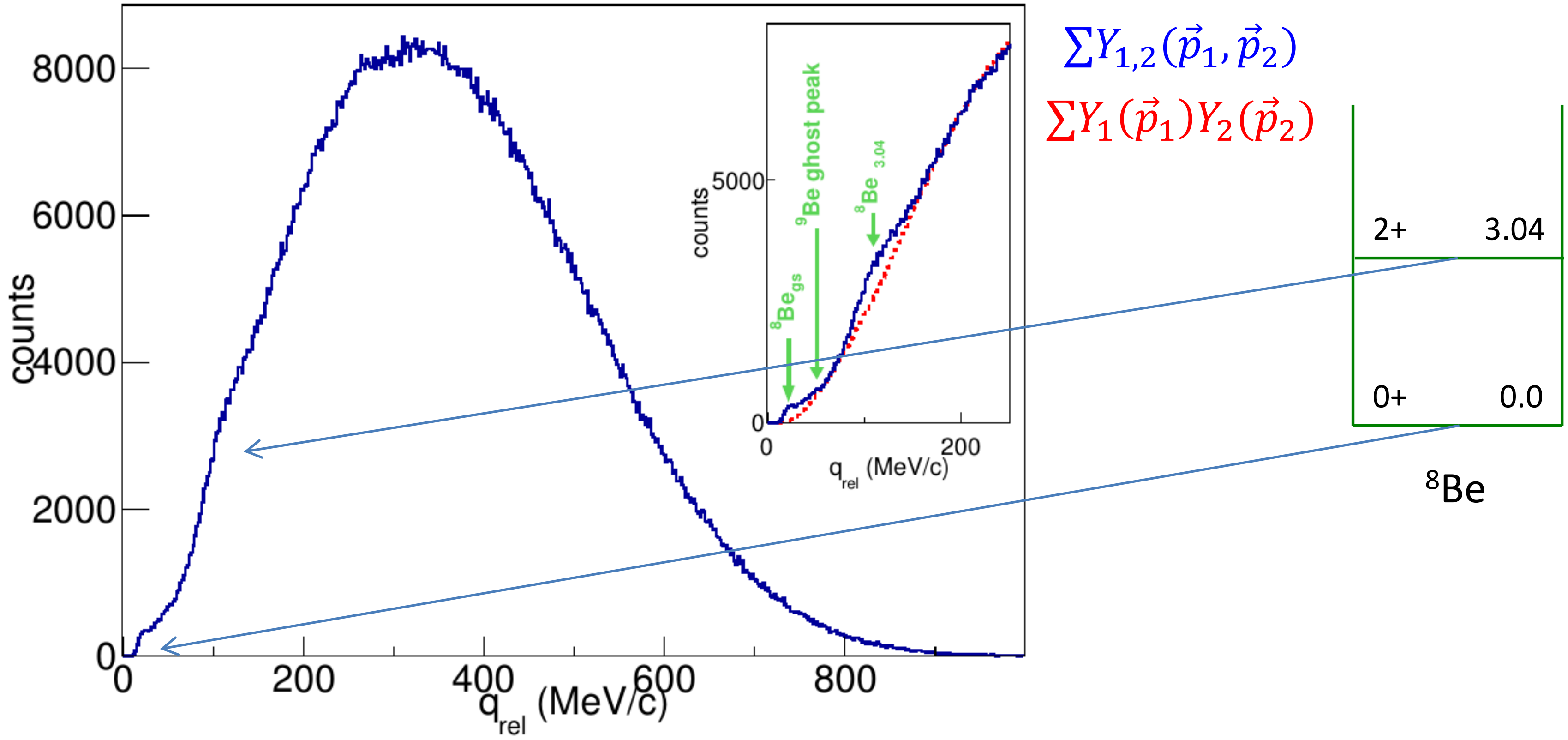
nuclear correlations

uncorrelated pairs

Coulomb anti-correlations<0

$$\sum Y_1(\vec{p}_1)Y_2(\vec{p}_2) = Y_{unco}(q_{rel})$$

(*Event mixing* method)



$\sum Y_{1,2}(\vec{p}_1,\vec{p}_2)$

$\sum Y_1(\vec{p}_1)Y_2(\vec{p}_2)$

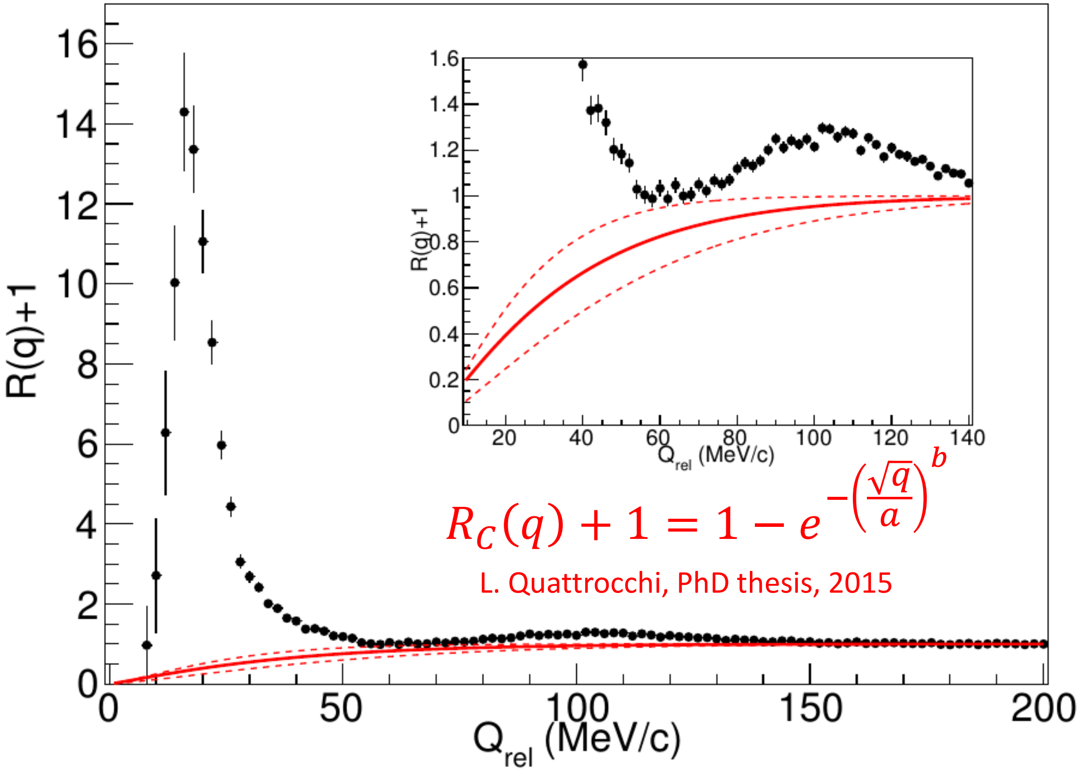
2α correlations in HICs → in-medium studies

$$\sum Y_{1,2}(\vec{p}_1,\vec{p}_2) = \boxed{Y_N(q_{rel})} + \boxed{Y_{unco}(q_{rel})} + \boxed{Y_C(q_{rel})}$$

nuclear correlations
uncorrelated pairs
Coulomb anti-correlations<0

$$R(q) + 1 = \frac{\sum Y_{1,2}(\vec{p}_1,\vec{p}_2)}{\sum Y_1(\vec{p}_1) Y_2(\vec{p}_2)}$$

(two particles *correlation function*)

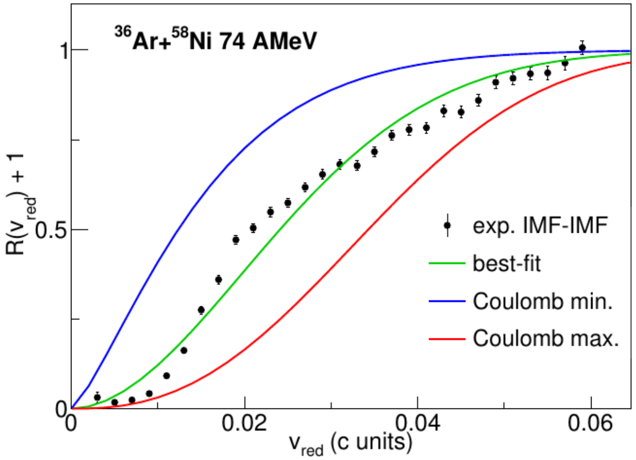


$$R_C(q) + 1 = 1 - e^{-\left(\frac{\sqrt{q}}{a}\right)^b}$$

L. Quattrocchi, PhD thesis, 2015

Example from *^{36}Ar+^{58}Ni collisions at 74 AMeV with INDRA*

Coulomb *anti-correlation* obtained from the non-resonant IMF-IMF correlations.



2α correlations in HICs → in-medium studies

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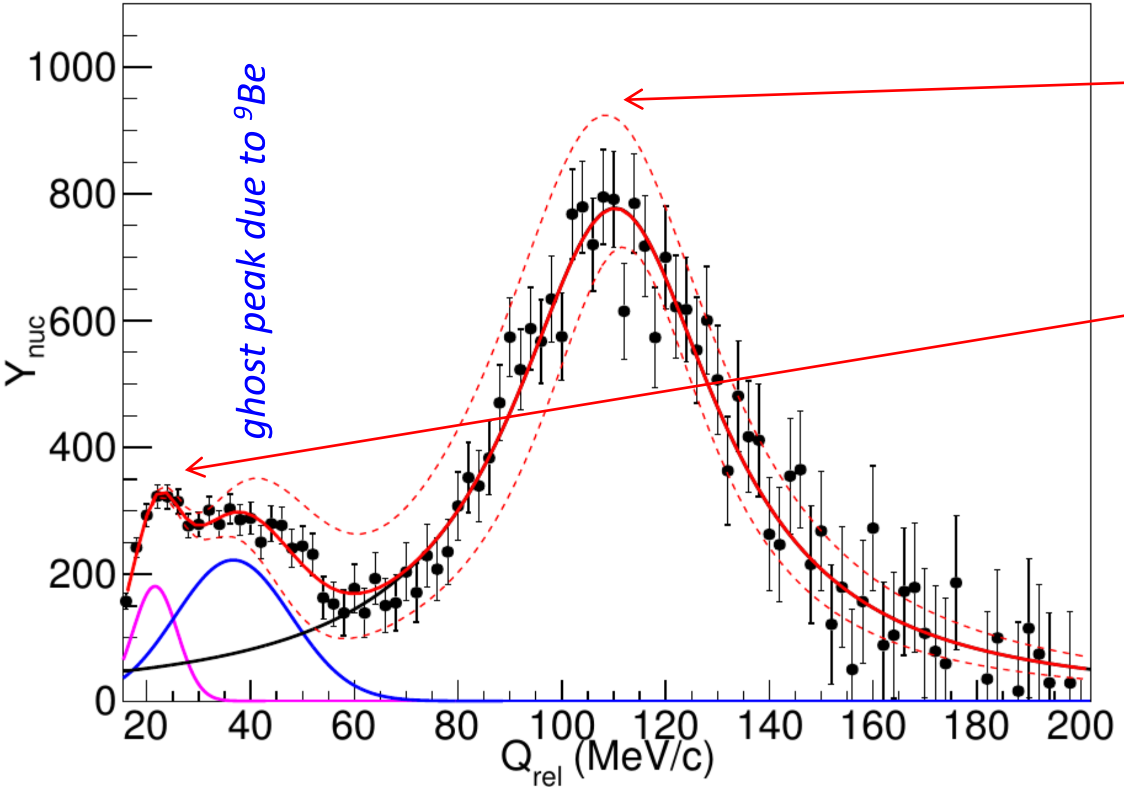
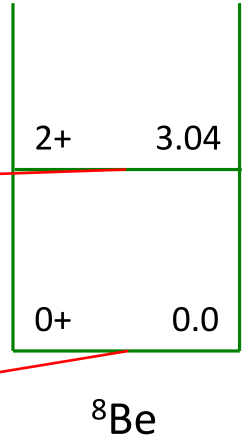
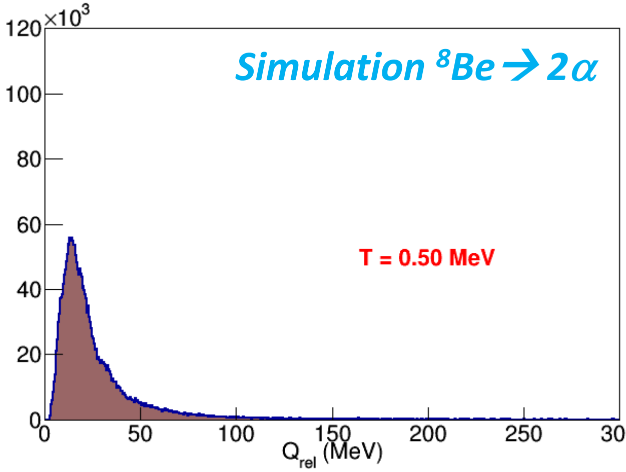
Nuclear part of the correlations → obtained by subtracting background and taking into account the coulomb anti-correlation effects:

$$Y_N(q_{rel}) = \sum Y_{1,2}(\vec{p}_1,\vec{p}_2) - Y_C(q_{rel}) - Y_{unco}(q_{rel}) =$$
$$\sum Y_{1,2}(\vec{p}_1,\vec{p}_2) - \left(1 + R_C(q)\right)\sum Y_1(\vec{p}_1)Y_2(\vec{p}_2)$$





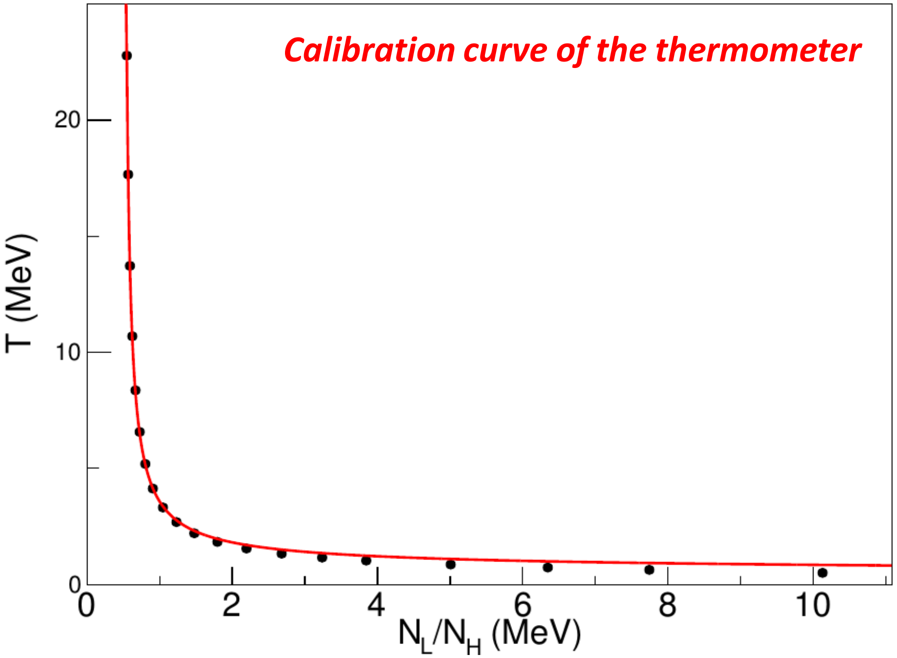


2α correlations in HICs → in-medium studies

Using of a couple of resonances of ^{8}Be (g.s. and 3.04 MeV) as nuclear thermometer → thermal model:

$$\frac{N_L}{N_H} = \frac{\int_L Y_N(q_{rel})dq_{rel}}{\int_H Y_N(q_{rel})dq_{rel}} = \frac{2J_L+1}{2J_H+1} e^{-\frac{\Delta E}{T}}$$

The population of the excited states is a good tool to extract the temperature of the *nuclear medium* in which the resonances are produced.



From the measured peak integrals at 32AMeV, 40AMeV, 52AMeV, 64AMeV, 74AMeV, 84AMeV and 95AMeV→ we found no consistency with a thermal equilibrium hypothesis → *extra-population* of the 3.04MeV state:

2α correlations in HICs → in-medium studies

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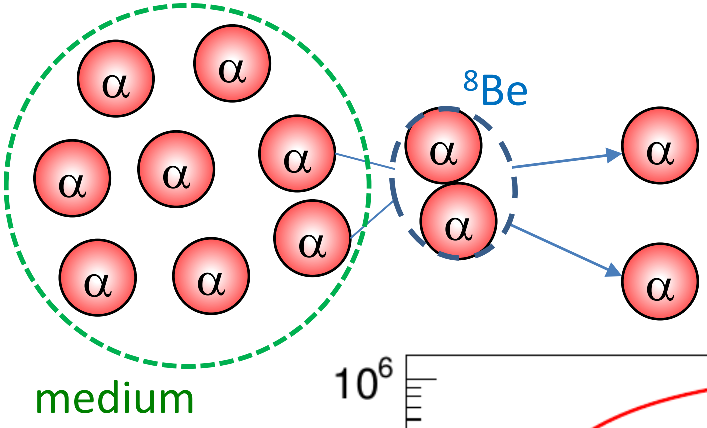
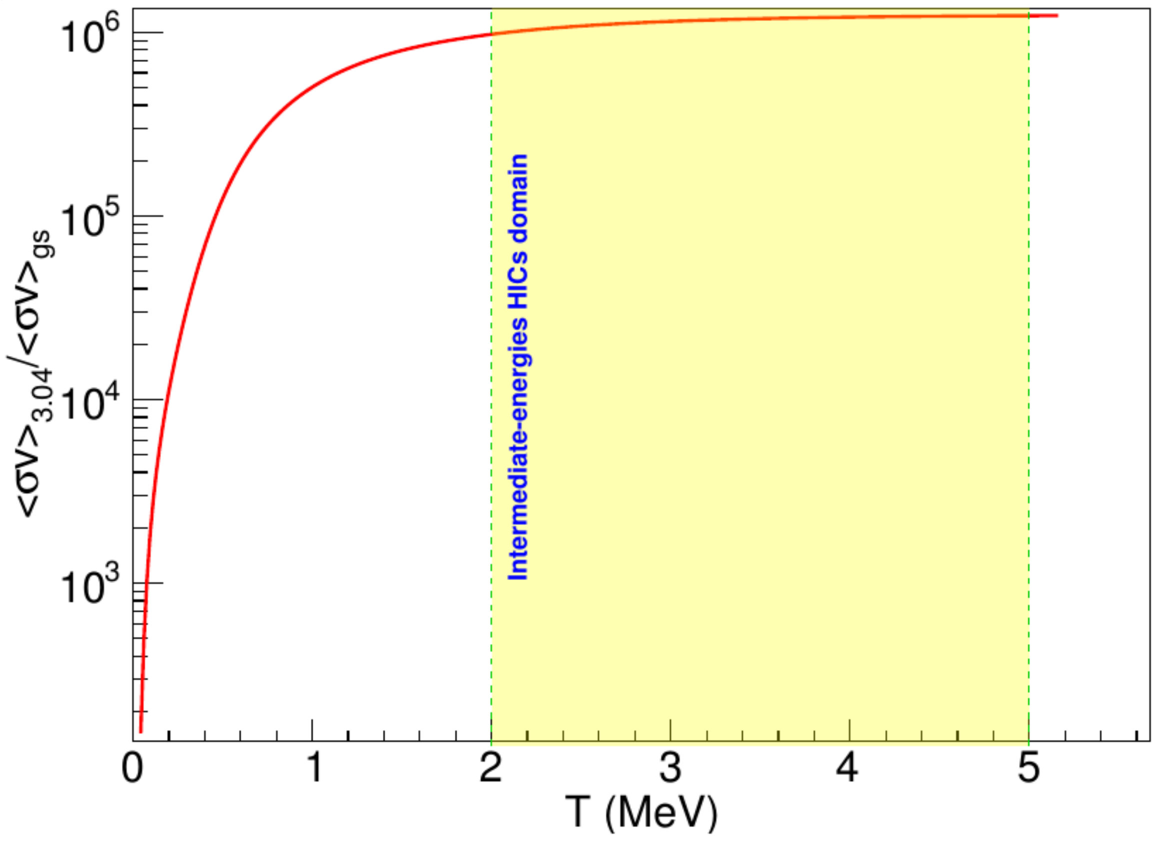
An interesting hypothesis:

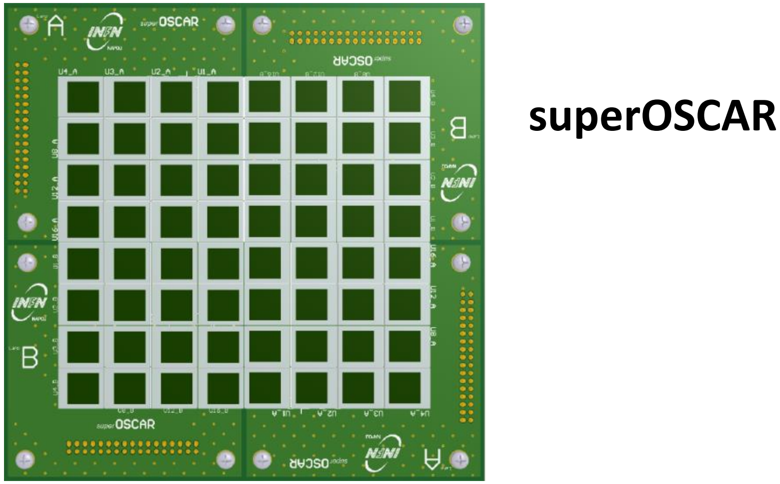


further contribution to ^{8}Be resonant production due to α-α *in-medium interactions* → the fusion through the 3.04 MeV state would be strongly dominant at the medium-temperatures values explored in intermediate energies HICs → *extra-population*!

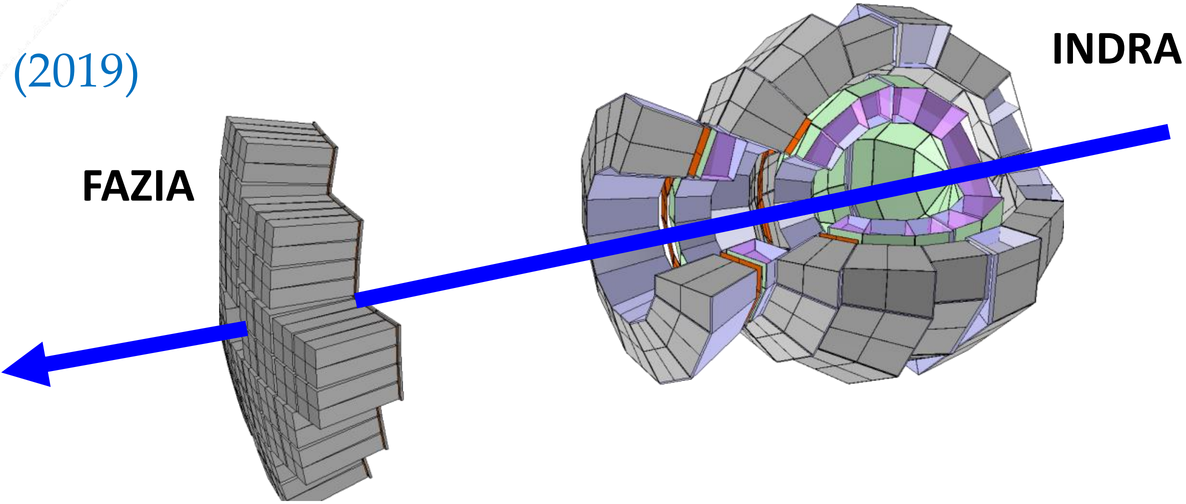


OSCAR: Odoscopio di Silici per le Correlazioni e le Analisi di Reazioni

A new modular hodoscope for the analysis of nuclear reactions.
SSSSD (20μm, 16 strips 3mm + 0.125mm interstrip) + 16 silicon pads



INDRA-FAZIA @ GANIL (2019)



Conclusions and Perspectives

- *Particle-particle* and *multi-particle correlations* are a powerful tool to explore *Nuclear Structure* and *Dynamics*;

- Correlations involving α *particles* → structure of *self-conjugated nuclei* and *clustering* phenomena;

- We studied the Hoyle state in ^{12}C by means of *3α correlations* using the $^{14}N(d,\alpha_2)^{12}C(hoyle)$ at 10.5 MeV → for obtaining a extremely *low background* we used the anti-telescope technique and we developed a new modular hodoscope, *superOSCAR* → We improved, of a factor 5, the present precision in the knowledge of the Hoyle state direct decay branching ratio (*recently accepted on Phys. Rev. Lett.*);

- *HICs at intermediate energies* → interesting example of how nuclear correlations are useful to study the interplay of Nuclear Structure and Dynamics → clustering in *sub-saturation density* regions (central collisions) → 2α correlations → ^{8}Be as *nuclear thermometer* → $^{36}Ar+^{58}Ni$ (32-95 AMeV) → extra-population of the 3.04 MeV state yield → *in-medium a-a interactions*?

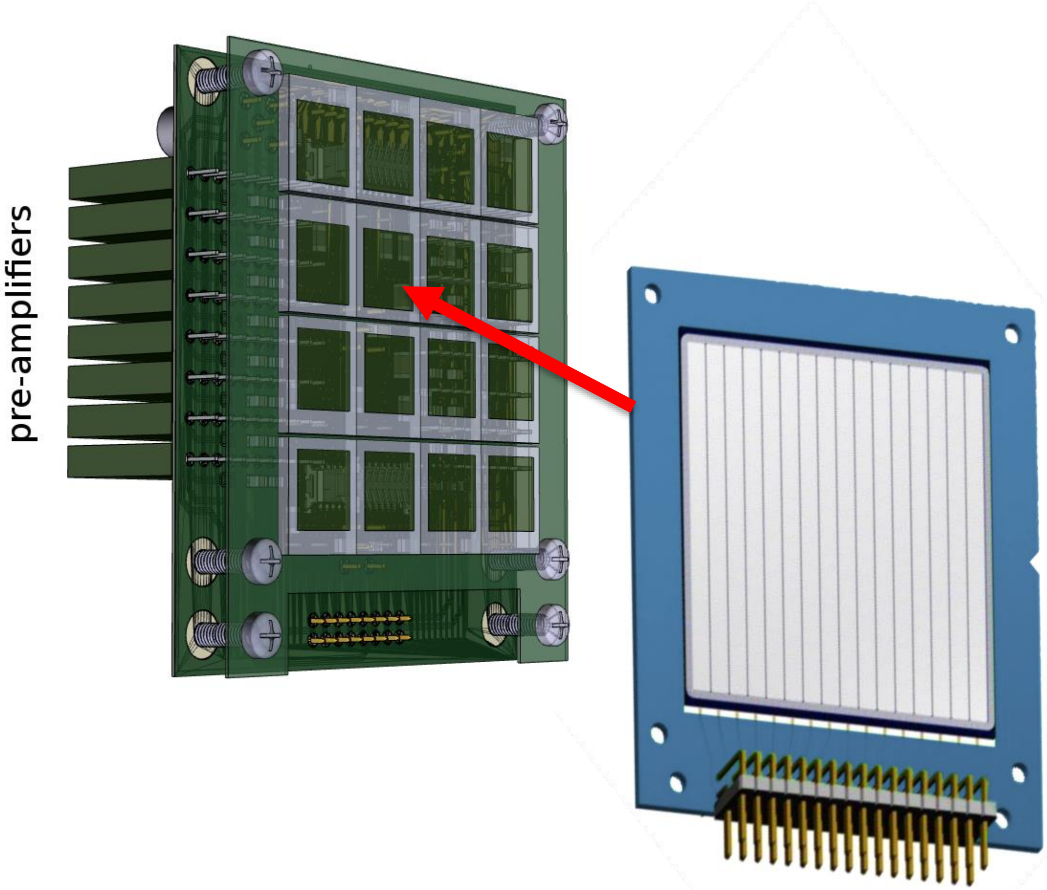
Thank you for your attention.

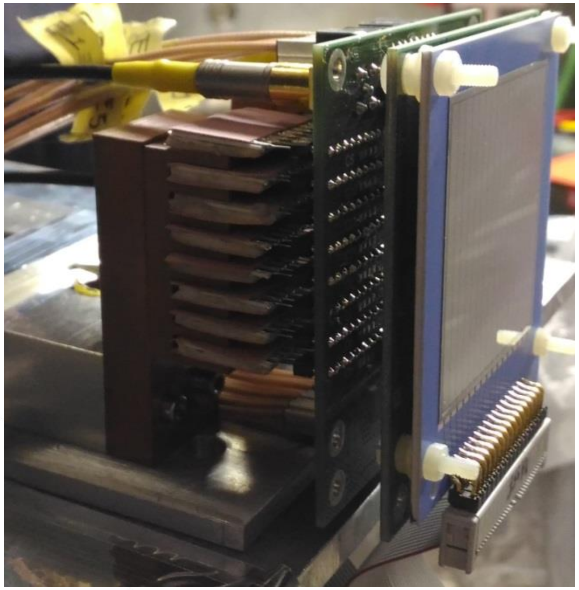
Further Slides

Development of new generation hodoscopes: OSCAR

OSCAR: Odoscopio di Silici per le Correlazioni e le Analisi di Reazioni

A new hodoscope for the analysis of nuclear reactions.
SSSSD (20μm, 16 strips 3mm + 0.125mm interstrip) + 16 silicon pads

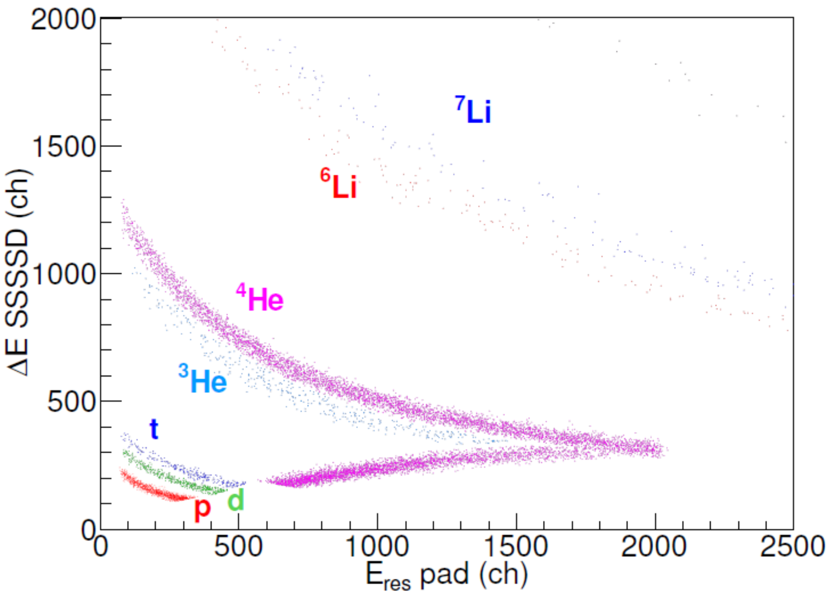




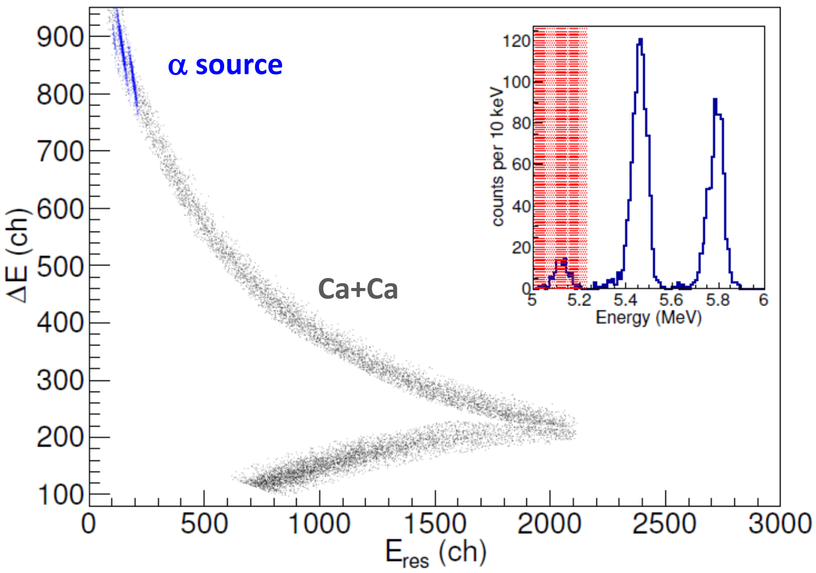
Developed with the INFN-Napoli SER.

- Plug-and-play connections
- on-board pre-amplifiers
- modular and compact detector
- low cross-talk levels and high resolutions

TEST di OSCAR ai LNS: ^{40,48}Ca+^{40,48}Ca at 35 A MeV, 52° LAB



Good particles identification up to lithium isotopes via the DE-E technique.



Identification of very low energy particles with very good energy resolution. (a dedicated experiment has been performed at LNS for studiyng the effects of the silicon non-uniformity on the particle identifications and energy resolutions.

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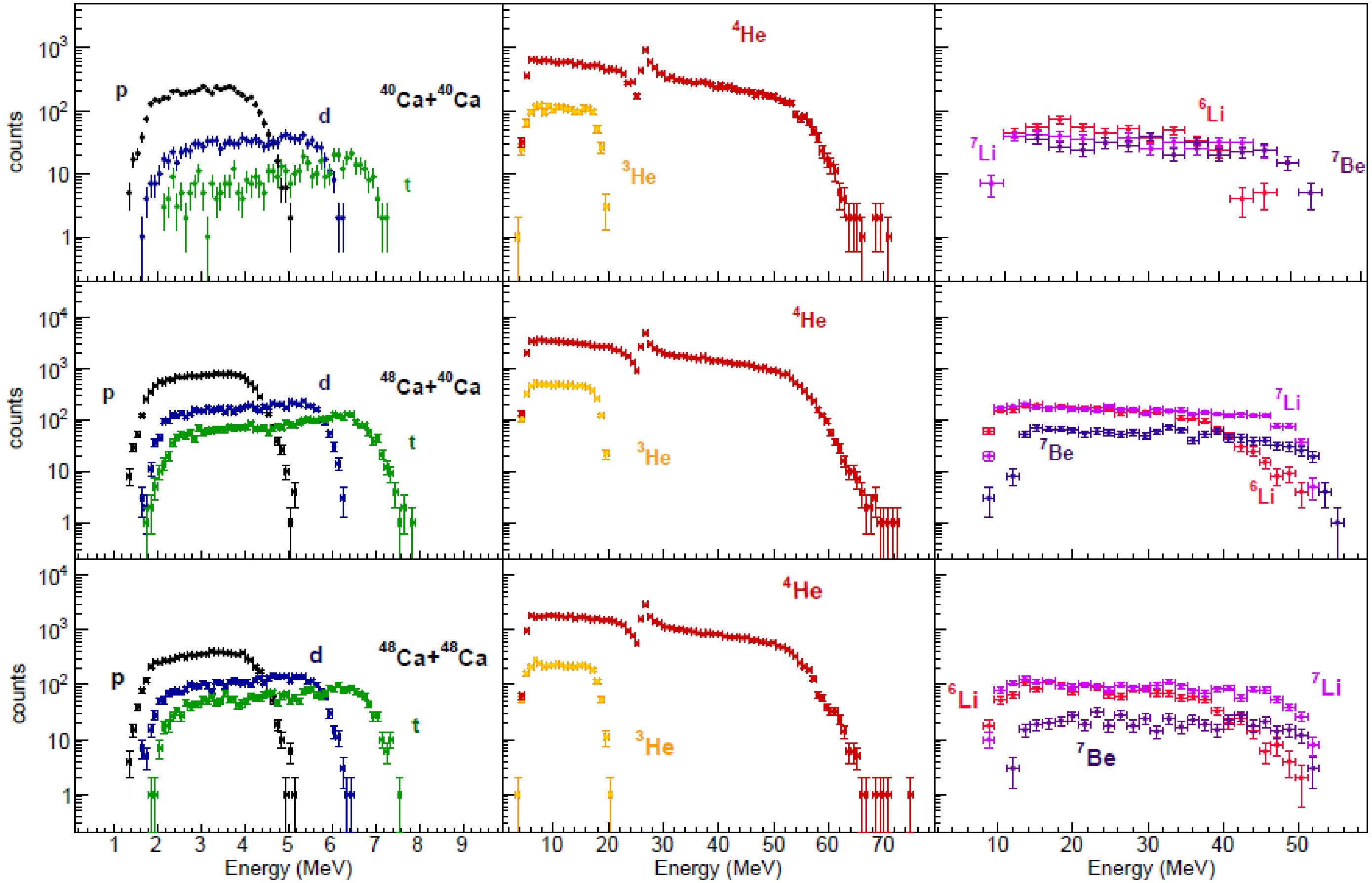
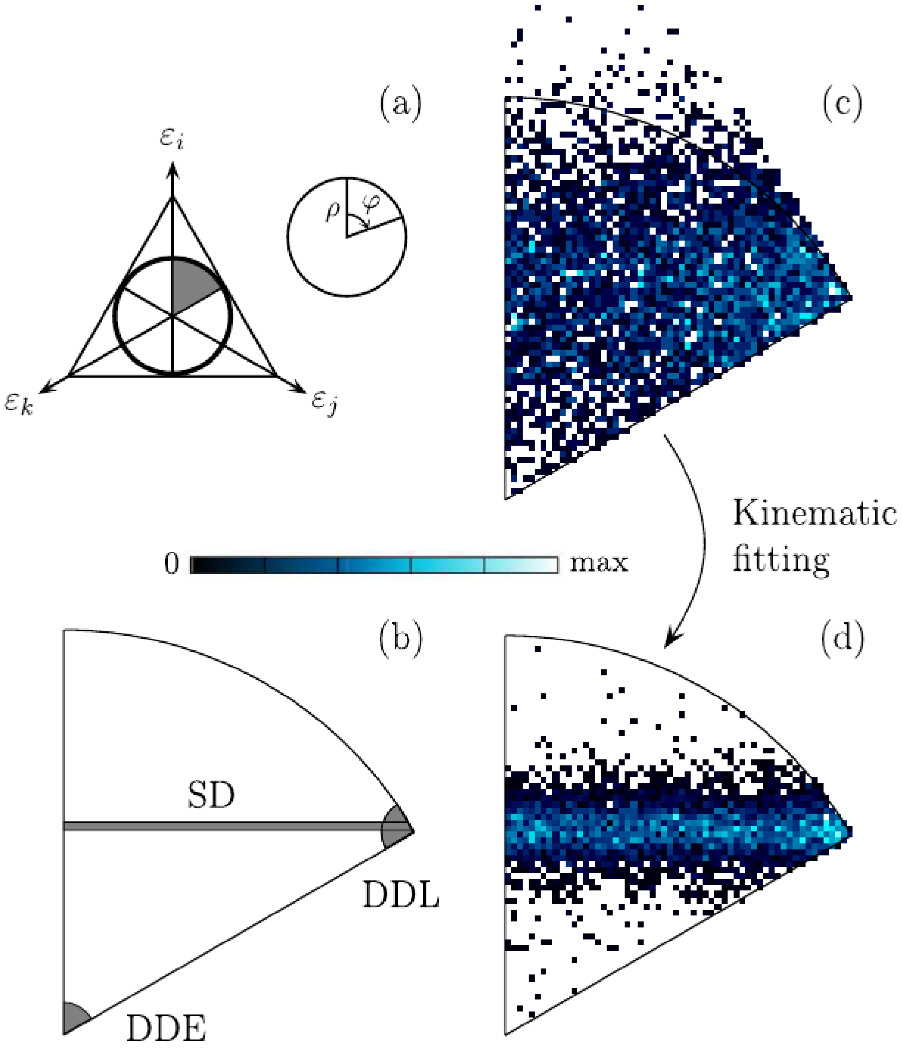
Energy spectra of the lightest identified fragments obtained in 48Ca+48Ca collisions at 35MeV/u

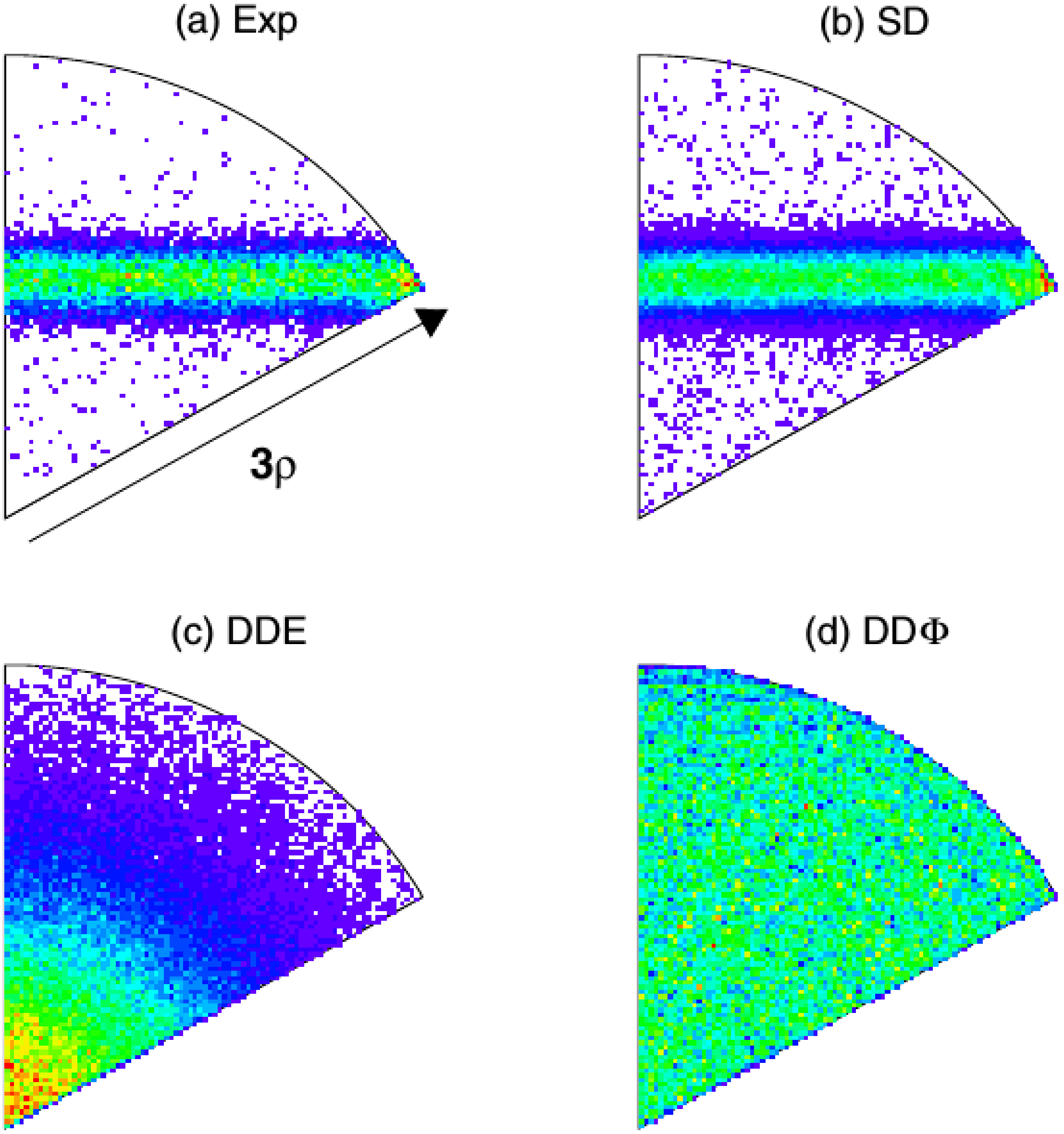


A route to SPES → development of high segmentated detectors with low detection thresholds and high modularity (ancillary detector).

to be submitted for publication…

^{12}C structure via the ^{14}N(d,α) reaction: the HOYLE experiment




(a) Exp
(b) SD
3ρ
(c) DDE
(d) DDΦ