III Incontro Nazionale di Fisica Nucleare
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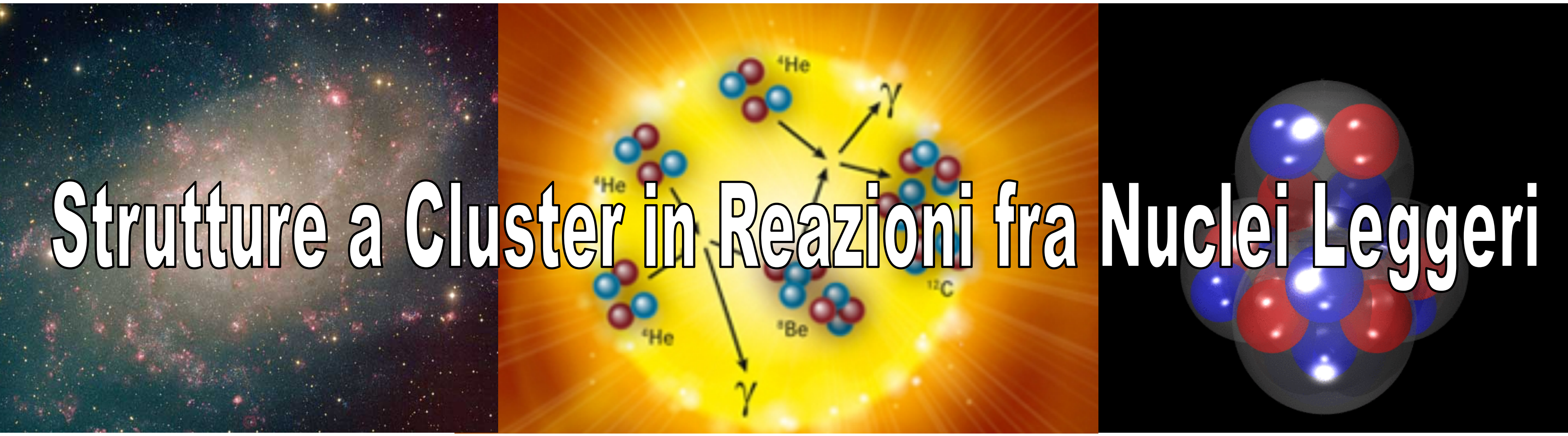

Strutture a Cluster in Reazioni fra Nuclei Leggeri

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Outline

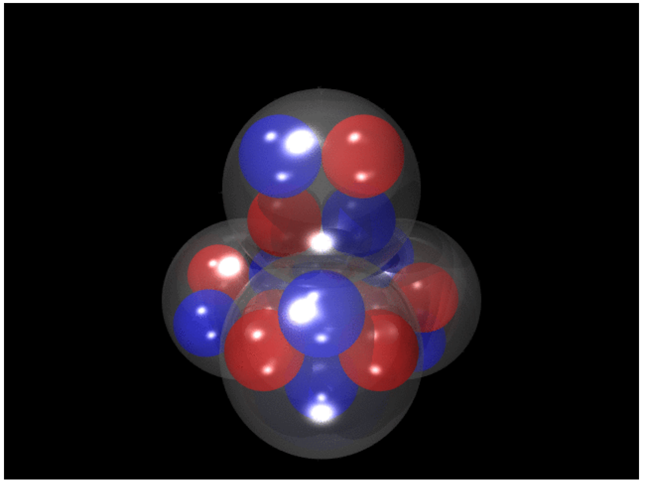
Clusters in the Trojan Horse Method for Nuclear Astrophysics

Triple alpha resonances in 12C and Efimov mechanism in nuclei

Role of Clusters in fusion reactions between light nuclei at low energy

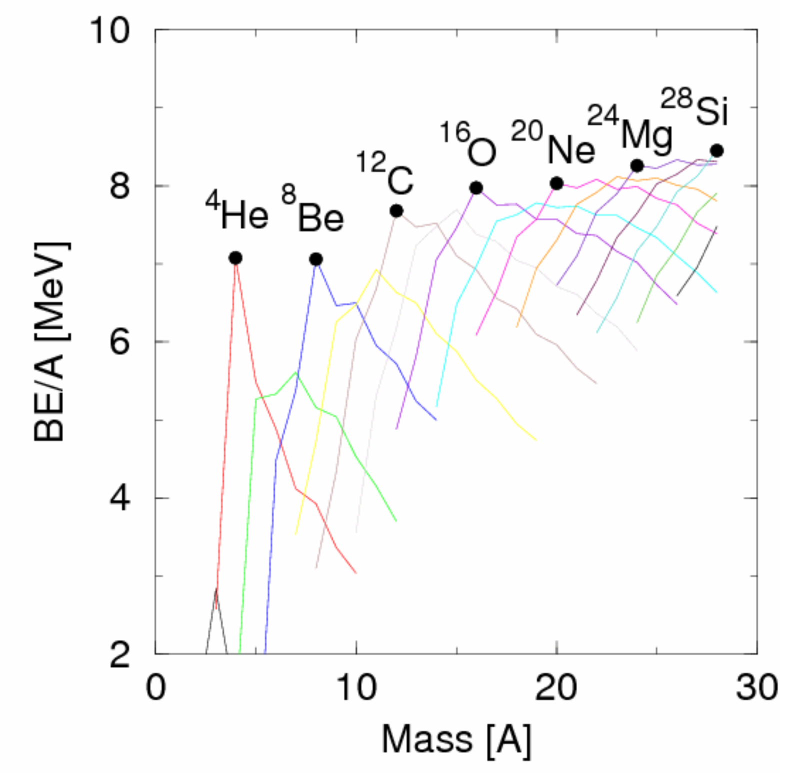
Clustering features

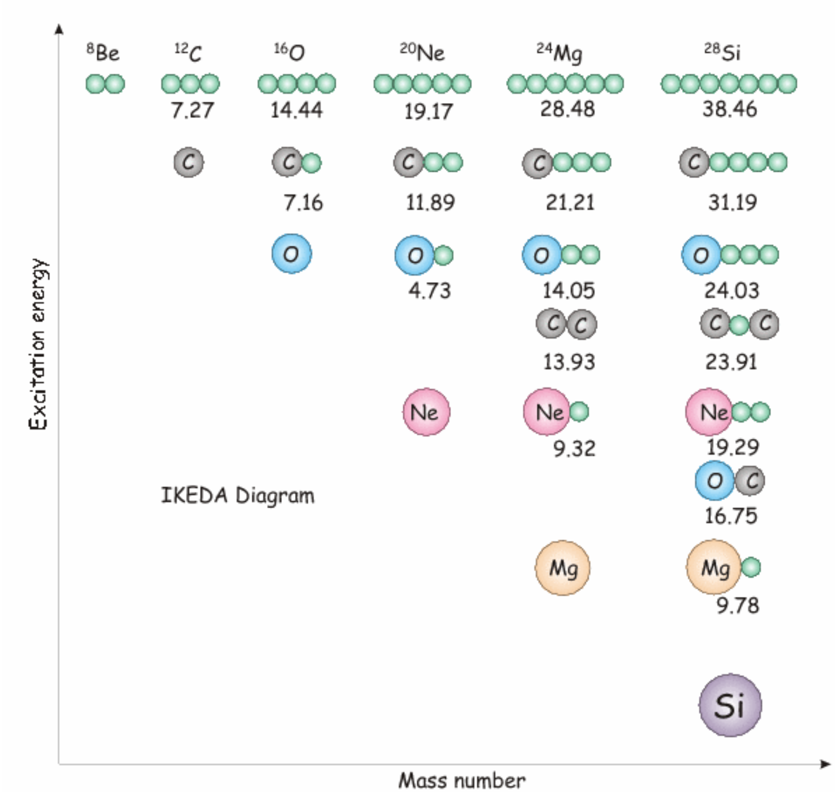
The concept of clustering has a long history. Even at the inception of nuclear science, even before the neutron was discovered, it was known that conglomerates of nucleons **(nuclear clustering)** were extremely important in determining the structure of light nuclei

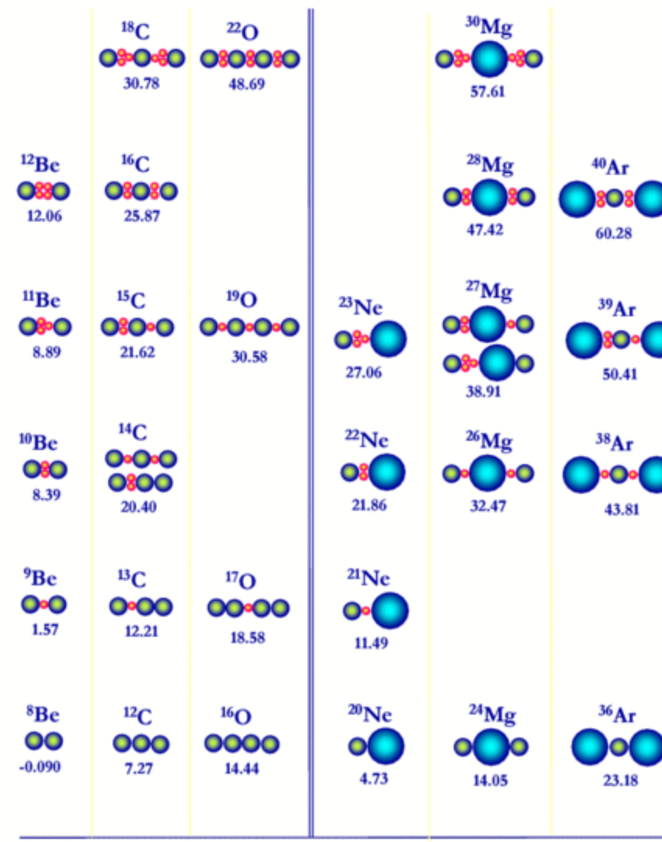


The discovery of alpha-decay of heavy-nuclei initiated the idea that clusters of nucleons (two protons and two neutrons) might be preformed prior to emission.

Binding energies are higher for systems with even-numbers of protons, and for nuclei with even and equal numbers of protons and neutrons the binding energy per nucleon is maximal (e.g. ^{4}He, ^{8}Be, ^{12}C.....). It should be observed that all of these nuclei can be considered to be composed of α-particles.







The cluster structure would expect to be manifest close to the cluster decay threshold. In order to be fully formed, the proximity of cluster states to the decay threshold is crucial. This is the message of what is known as the Ikeda diagram (Ikeda et al., 1968)

Quasi-free processes: a way to probe clustering in light nuclei

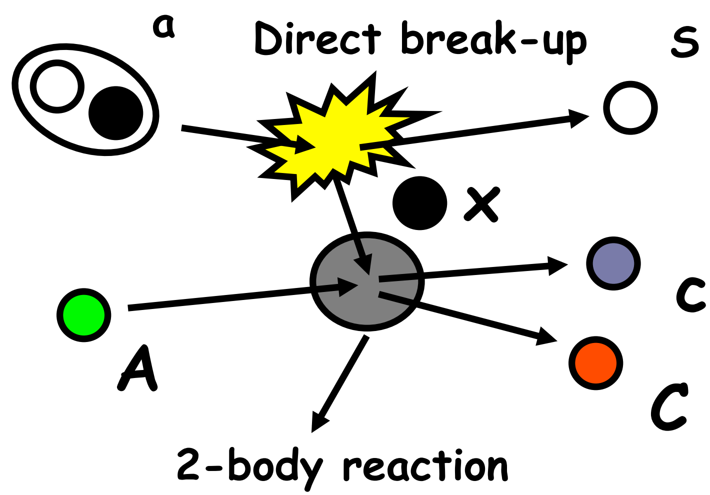
Quasi-free scattering and reactions to investigate the cluster structure in light nuclei.

$A + a \rightarrow c + C + s$ a: $x \oplus s$ clusters

Quasi-free mechanism

✓ only x - A interaction

✓ s = spectator ($p_s \sim 0$)



The Impulse Approximation factorizes the three-body cross-section as:

$$\frac{d^3\sigma}{d\Omega_c \, d\Omega_C \, dE_c} = P \; KF \cdot \left|\Phi(p_s)\right|^2 \frac{d\sigma^N}{d\Omega}$$

KF kinematical factor

$|\phi|^2$ momentum distribution of *s* inside *a*

$d\sigma^N/d\Omega$ Nuclear cross section for the $A+x \rightarrow C+c$ reaction

P clustering probability

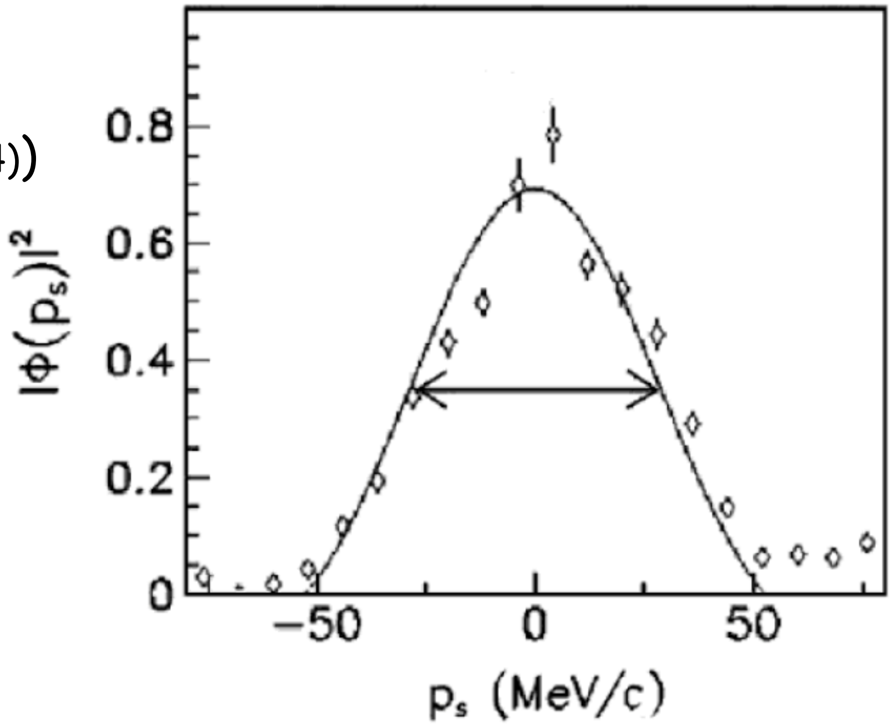
Once we know the $\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c}$ and $\frac{d\sigma^N}{d\Omega}$ from independent experiments

we calculate KF, we compare the shape of $|\Phi(p_s)|^2$ with the expected behaviour

if clustering exists, we can estimate **P**.
In the 80's, this technique was applied to ^{6}Li = a ⊕ d (B = 1.47 MeV).

The ^{6}Li(^{6}Li,aa) ^{4}He at 5.9 MeV
(M. Lattuada, C. Spitaleri et al., Il Nuovo Cimento (1984))

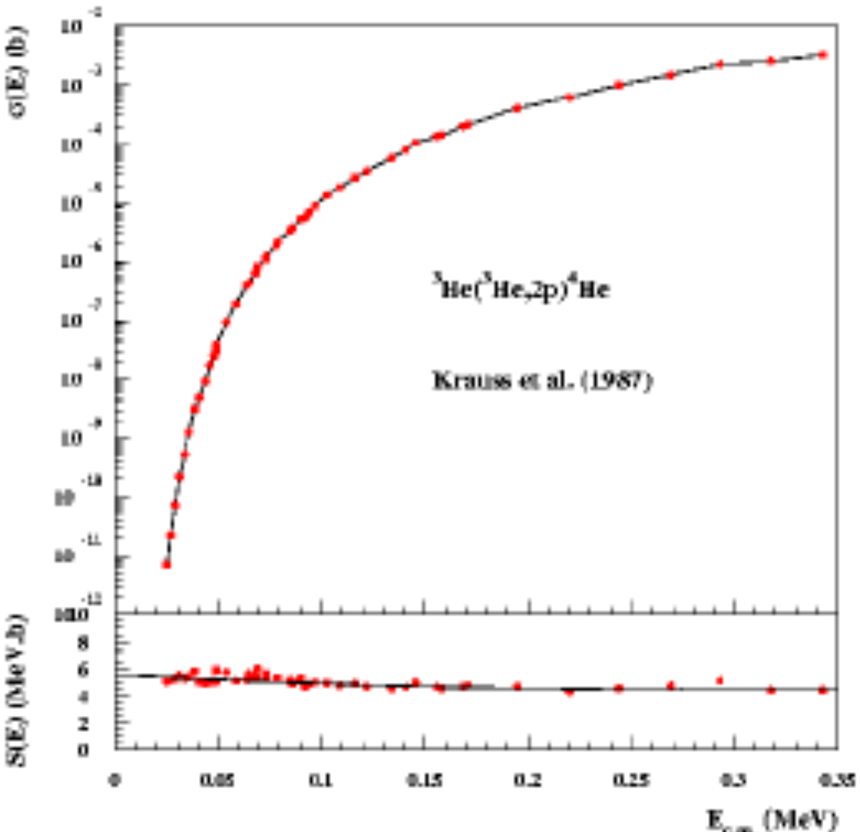
^{6}Li clustering description confirmed by the agreement between experimental and theoretical curves



Nuclear clusters as virtual projectile/targets for nuclear astrophysics: the THM

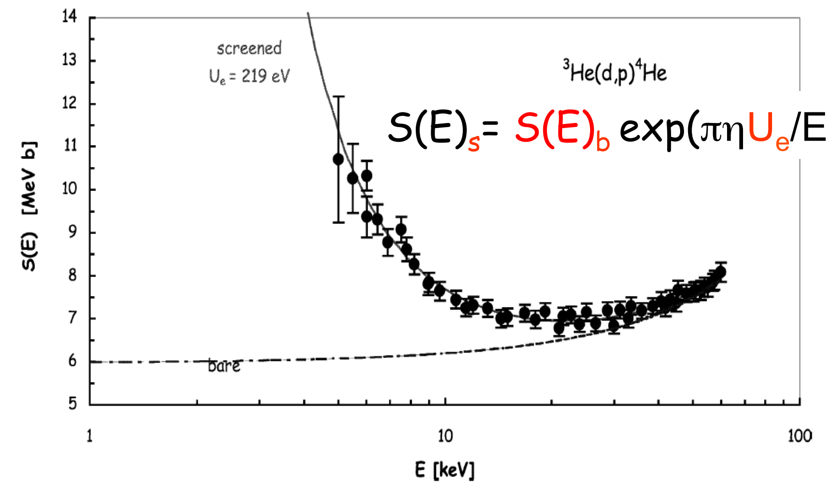
The THM is an indirect method to measure cross-sections at ultra-low energies overcoming the main problems of direct measurement:

Coulomb suppression,



$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

Electron screening



$$S(E)_s = S(E)_b \exp(\pi\eta U_e/E)$$

Trojan Horse Method

Basic principle: astrophysically relevant two-body σ from quasi-free contribution of an appropriate three-body reaction

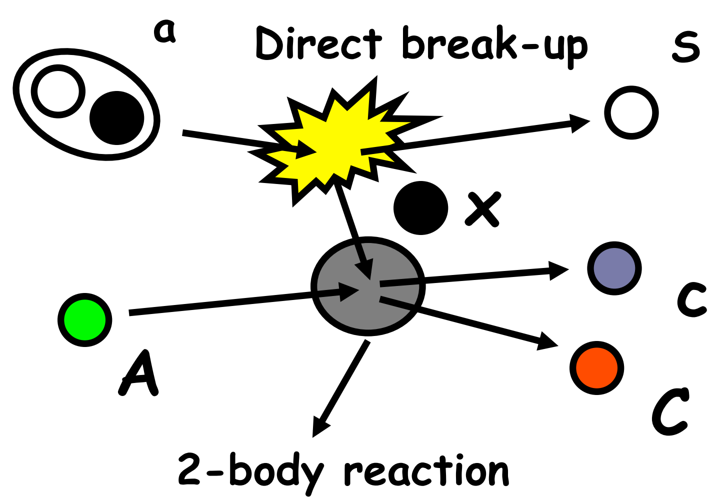
$$A + a \rightarrow c + C + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow c + C$$

a: x ⊕ s clusters

Quasi-free mechanism

✓ only *x* - *A* interaction

✓ *s* = spectator (p_s~0)



$E_A > E_{Coul} \Rightarrow$ NO Coulomb suppression

NO electron screening

$$E_{q.f.} = E_{ax} = m_x/(m_x + m_A)E_A - B_{x\text{-}s} \pm \text{intercluster motion}$$

$B_{x\text{-}s}$ ↓ plays a key role in compensating for the beam energy → $E_{q.f.} \approx 0$!!!

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	
1	$^{7}Li(p,\alpha)^{4}He$	$^{2}H(^{7}Li,\alpha\,\alpha)n$	19-22	15.122	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC,1999, Lattuada *et al.* ApJ, 2001
2	$^{7}Li(p,\alpha)^{4}He$	$^{7}Li(^{3}He,\alpha\,\alpha)d$	33	11.853	CYCLOTRON, Rez, Praha	Tumino *et al.* EPJ, 2006
3	$^{6}Li(p,\alpha)^{3}He$	$^{2}H(^{6}Li,\alpha\,^{3}He)n$	14,25	1.795	TANDEM 13 MV LNS-INFN, Catania	Tumino *et al.* PRC, 2003
4	$^{9}Be(p,\alpha)^{6}Li$	$^{2}H(^{9}Be,\alpha\,^{6}Li)n$	22	-0.099	TANDEM CIAE, Beijing TANDEM 13 MV LNS-INFN, Catania	Wen *et al.* PRC, 2008, Wen et al. JPG 2011
5	$^{11}B(p,\alpha)^{8}Be$	$^{2}H(^{11}B,\alpha\,^{8}Be)n$	27	6.36	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC, 2004, Lamia *et al.* JPG, 2011
6	$^{15}N(p,\alpha)^{12}C$	$^{2}H(^{15}N,\alpha\,^{12}C)n$	60	2.74	CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRC, 2008
7	$^{18}O(p,\alpha)^{15}N$	$^{2}H(^{18}O,\alpha\,^{15}N)n$	54	1.76	(CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRL 2008,
8	$^{19}F(p,\alpha)^{16}O$	$^{2}H(^{19}F,\alpha\,^{16}O)n$	50	8.11	TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* ApJ Lett., 2011)
9	$^{17}O(p,\alpha)^{14}N$	$^{2}H(^{17}O,\alpha^{14}N)n$	45	-1.032	TANDEM 13 MV LNS-INFN, Catania TANDEM 11 MV Notre Dame	Sergi et al. PRC (R), 2010

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
10	$^{18}F(p,\alpha)^{15}O$	$^{2}H(^{18}F,\alpha^{15}O)n$	48		CYCLOTRON CNS-RIKEN, Tokyo	Cherubini et al. PRC 2015 R.G. Pizzone et al. EPJA 201
11	$^{10}B(p,\alpha)^{7}Be$	$^{2}H(^{10}B,\alpha^{7}Be)n$	27		TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. PRC 2014
12	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	5 4.8	22.372	TANDEM Demoscritos,Atene TANDEM, IRB, Zagreb	Cherubini *et al.* ApJ, 1996 Spitaleri *et al* .PRC, 2001
13	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$			CYCLOTRON Rez, Praha	Pizzone et al. PRC, 2011
14	$^{3}He(d,\alpha)^{1}H$	$^{6}Li(^{3}He,p^{4}He)^{4}He$	5,6	16.878	DYNAMITRON, Bochum	La Cognata *et al.* 2005
15	$^{2}H(d,p)^{3}H$	$^{2}H(^{6}Li,p^{3}He)^{4}He$	14	2.59	DYNAMITRON, Bochum	Rinollo *et al.* EPJ 2005
16	$^{2}H(d,p)^{3}H$	$^{2}H(^{3}He,p^{3}H)^{1}H$	18	-1.46	CYCLOTRON, Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
17	$^{2}H(d,n)^{3}He$	$^{2}H(^{3}He,n^{3}He)^{1}H$	18	-2.224	CYCLOTRON Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
18	$^{9}Be(p,d)^{8}Be$	$^{9}Be(d,d^{8}Be)n$			TANDEM 13 MV CIAE, Beijing	Preliminary results
19	$^{6}Li(n,a)^{3}H$	$^{2}H(^{6}Li, t\ \alpha)^{1}H$	14	2.224	TANDEM 13 MV LNS-INFN, Catania	Tumino et al.,EPJ A 2005 Gulino et al., JPG 2010

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
20	$^{17}O(n,a)^{14}C$	$^{17}O(n, a^{14}C)^{1}H$	43.5	-0.40 7	TANDEM 11 MV Notre Dame TANDEM 13 MV LNS-INFN, Catania	Gulino et al. PRC(R) 2013
21	$^{13}C(a,n)^{16}O$	$^{13}C(^{6}Li, a\ n)^{16}O$			TANDEM FSU, Tallaassee, Florida, USA	La Cognata et al. PRL 2013
22	$^{12}C(^{12}C,a)^{20}Ne$ $^{12}C(^{12}C,p)^{23}Na$	$^{12}C(^{16}O,a^{20}Ne)^{4}He$ $^{12}C(^{14}N,a^{20}Ne)^{2}H$ $^{12}C(^{14}N,p^{23}Na)^{2}H$			TANDEM 13 MV Bucharest,Catania	Preliminary results
23	$^{12}C(a,a)^{12}C$	$^{12}C(^{6}Li, a\ ^{12}C)^{2}H$	20	0	TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. EPJ 2000
24	$^{1}H(p,p)^{1}H$	$^{2}H(p,pp)n$	5,6	2,224	CYCLOTRON ATOMKI,Debrecen TANDEM IRB, Zagreb TANDEM 13 MV LNS-INFN, Catania TANDEM 5 MV Napoli University	Tumino et al. PRL 2007 Tumino et al. PRC 2008
25	$^{7}n(^{7}Be,a)^{4}He$	$^{2}H(^{7}Be,aa)^{1}H$			TANDEM LNL-INFN	Under analysis

Trojan Horse Method For Resonant Reactions

The $A + a(x+s) \rightarrow F^*(c + C) + s$ process is a transfer to the continuum where particle x is the transferred particle

Standard R-Matrix approach cannot be applied to extract the resonance parameters → Modified R-Matrix is introduced instead

In the case of a resonant THM reaction the cross section takes the form

$$\frac{d^2\sigma}{dE_{Cc}\, d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\, |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) that can be easily calculated → The resonance parameters can be extracted and in particular the strenght

IMPORTANT: reduced widths are the same for the extraction of the S(E) factors → From the fitting of the experimental THM cross section they can be obtained and used to deduce the OES S(E) factor.

$^{13}C + \alpha \rightarrow n + ^{16}O$: recent experiment at FSU

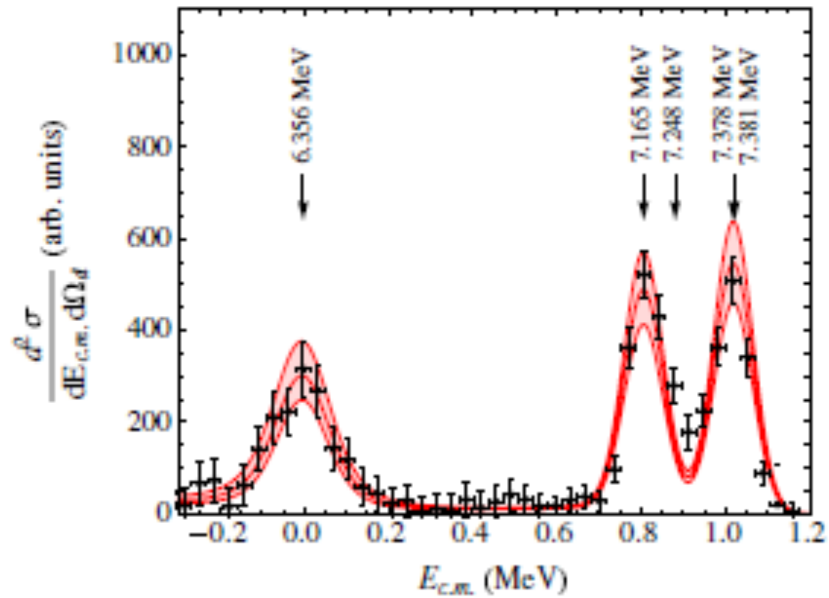
Neutron source for the main component of the s-process, responsible for the production of most nuclei in the mass range 90<A<204

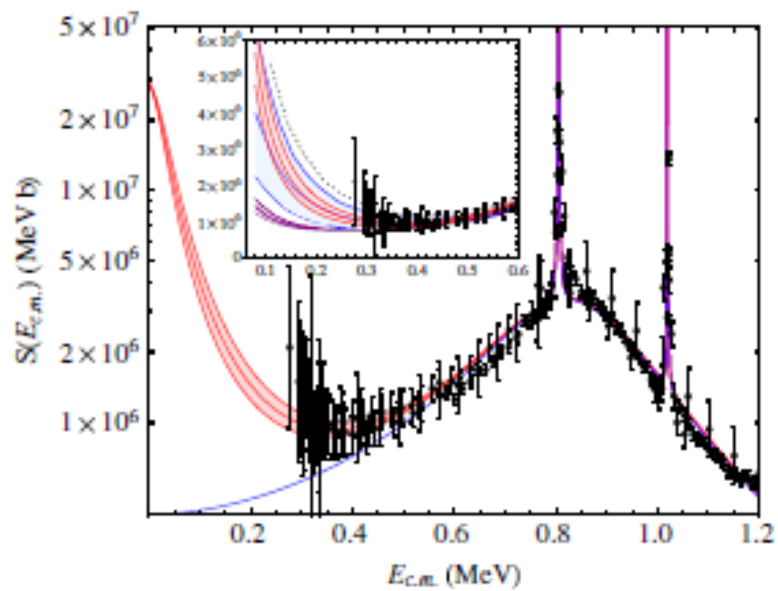
Active in He-burning shell in AGB from 140 to 230 keV → importance of the higher energy tail of the -3 keV resonance

its new partial width and ANC

$$\Gamma_n^{1/2^+} = 83^{+9}_{-12}\ \text{keV}$$

$$(\tilde{C}^{^{17}O(1/2^+)}_{\alpha-^{13}C})^2 = 6.7^{+0.9}_{-0.6}\ \text{fm}^{-1}$$





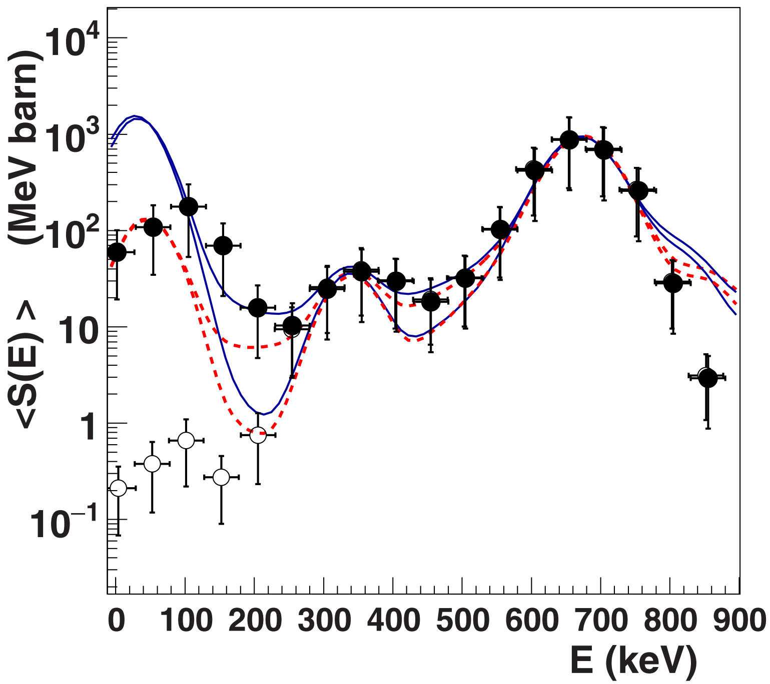
Reaction rate increases by a factor 3 in the relevant region:
→30% variation in the abundance of

^{86}Kr, ^{87}Rb, ^{96}Zr, and ^{142}Ce

due to the increased neutron density!

M. La Cognata et al., PRL 2013
M. La Cognata et al., ApJ 2014

The $^{18}F(p,\alpha)^{16}O$ Reaction @ CRIB - CNS - RIKEN and @ Cyclotron Laboratory, TAMU using a ^{18}F RIB



The $^{18}F(p,\alpha)^{15}O$ astrophysical S factor from the present experiment.

<u>*Solid circles*</u>: THM experimental data with the assumption of $J^\pi = 3/2^+$ for the resonance at E=6460 keV (upper limit)

<u>*Open circles*</u>: $^{18}F(p,\alpha)^{15}O$ astrophysical S factor corresponding to the assumption of $J^\pi = 5/2^-$ (lower limit)

S. Cherubini et al. PRC 92 (2015) 015805
R.G. Pizzone et al. EpJ A (2016)

Blue solid and red dashed lines: calculations reported and discussed in Beer et al. PRC 83 (2011) 042801 smeared to the present experimental resolution (σ = 53 keV). The difference is given by the alternative interference pattern adopted in the calculations.

Each pair of curves represents the upper and lower limit for each calculation

Around 700 keV: normalization region

Elsewhere: fair agreement with the dashed lines if $J^\pi = 3/2^+$ is assumed

Triple alpha resonances in the $^6Li+^6Li \rightarrow 3\alpha$ at low energy

Coincidence measurement of the $^6Li + ^6Li \rightarrow 3\alpha$ reaction at 3.1 MeV of beam energy

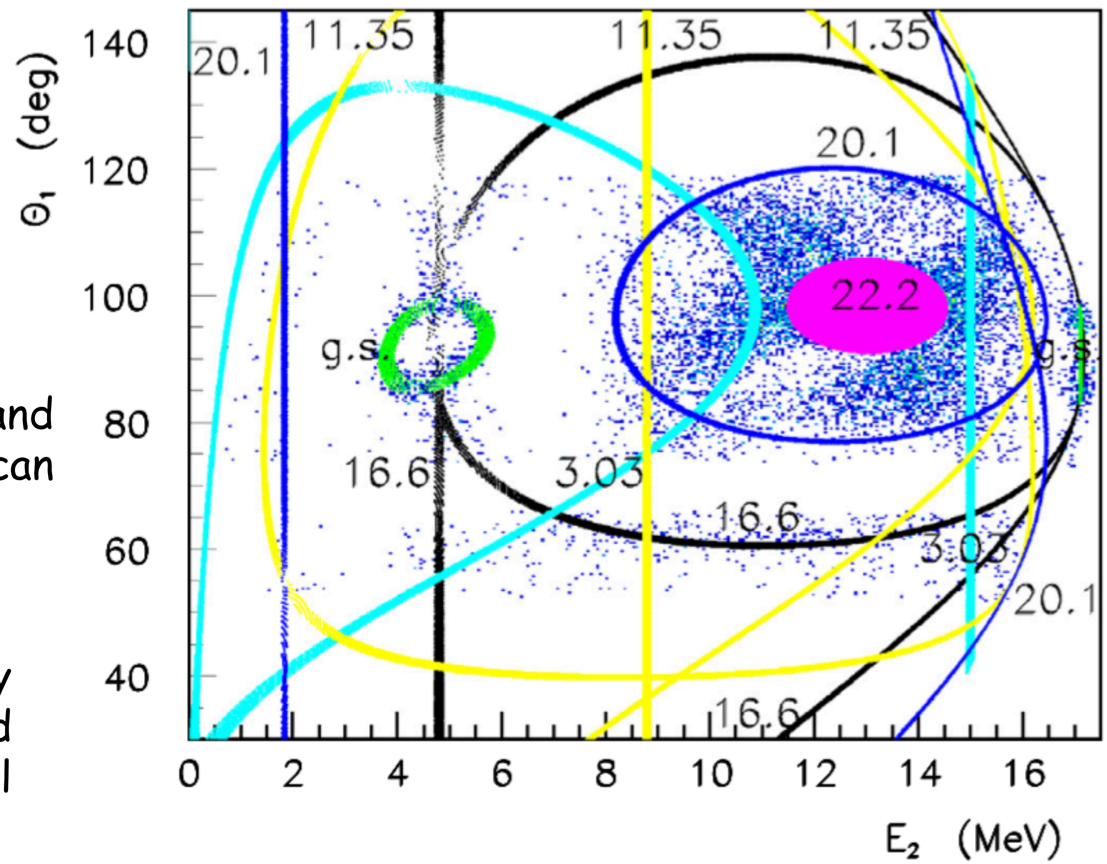
Results: existence of α-trimers at an excitation energy of ^{12}C of about 29.6 MeV ($^6Li + ^6Li$ threshold: 28.17 MeV; center-of-mass beam energy at half target: 1.4 MeV

Two-dimensional plots θ_1 vs. E_2 for a fixed value of θ_2=60°

Intersection between lines:

events with correlated α's fed by two and even three ^8Be at the same time can exist.

From this figure, though very illustrative, it is not straightforward to gather a global information from all experimental data.



A. Tumino et al. PLB (2015) 59

Hyperspherical formalism for the low-energy three-body problem:

to better investigate the correlation between the three α particles from the available data in a whole,

$$\vec{p}_{ij} = \vec{p}_i - \vec{p}_j,$$
$$\vec{p}_{k,ij} = \vec{p}_k - \frac{1}{2}(\vec{p}_i + \vec{p}_j).$$

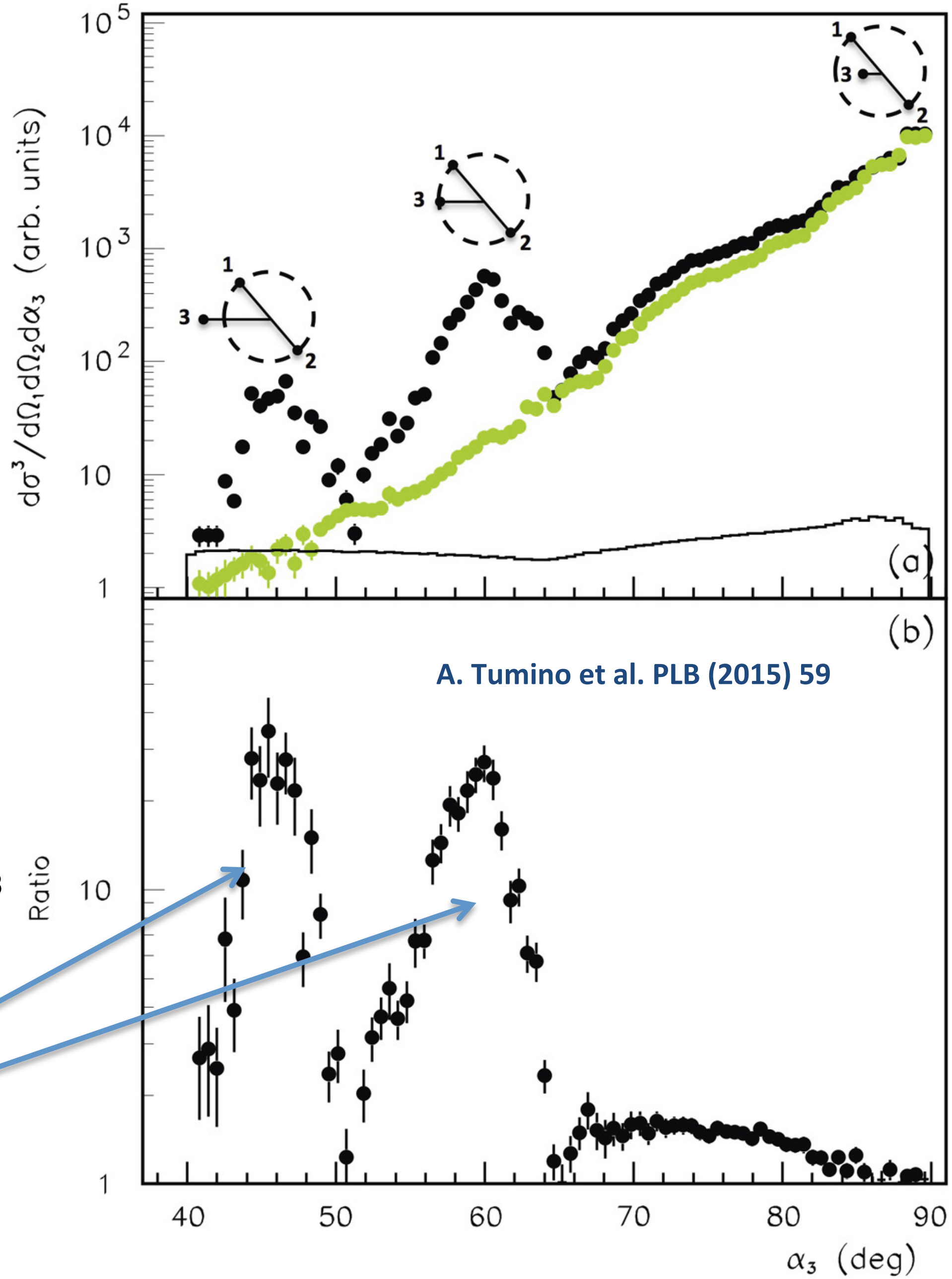
Jacobi momenta

$$\alpha_k = \arctan\left(\frac{\sqrt{3}p_{ij}}{2p_{k,ij}}\right)$$

Delves hyperangle

where (i, j,k) is a permutation of (1,2,3) and p_{ij} and $p_{k,ij}$ are the magnitudes of the momentum vectors. The range of α_k is from 0 to $\pi/2$

k is the undetected third α particle. Thus $\alpha_k = \alpha_3$



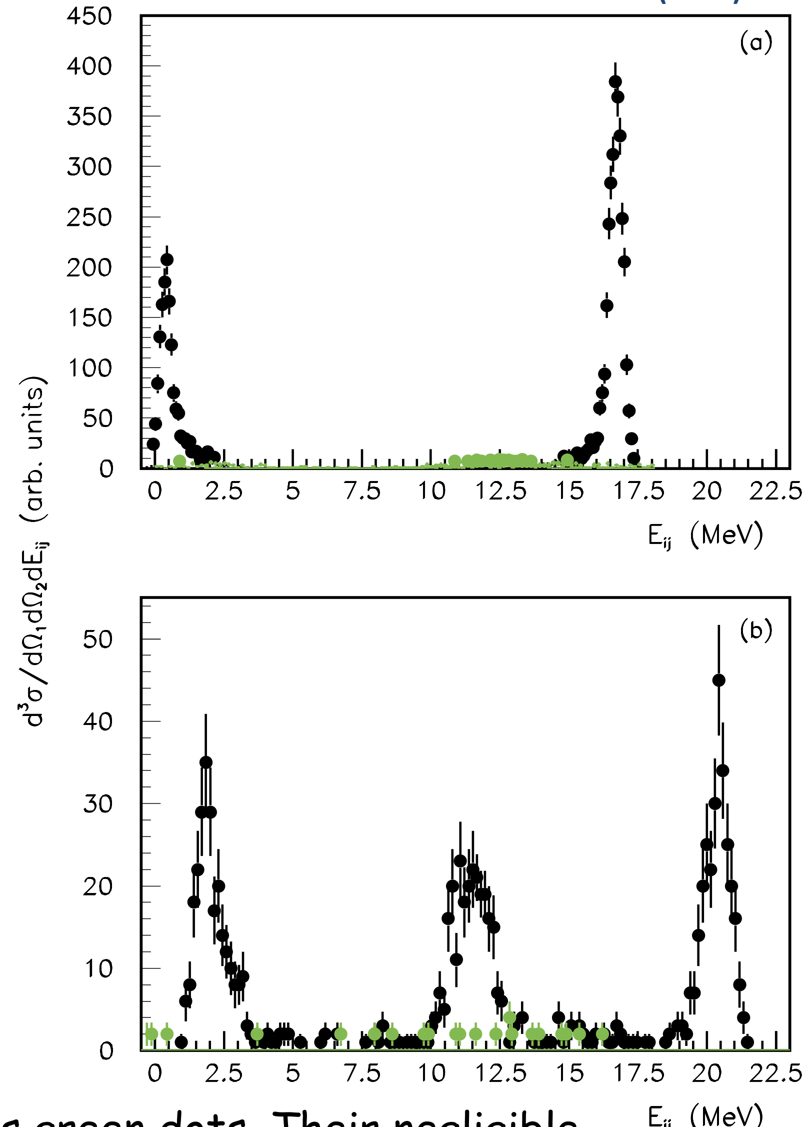
Signature of triple α correlation?

Events within those peaks were projected onto the Eij (i, j = 1,2,3) relative energy axis:

ground state and 16.62 MeV state of ^{8}Be (fed twice with respect to the 90 keV)

three ^{8}Be states at 20.1, 11.35 and 3.03 MeV, taking advantage of their huge widths

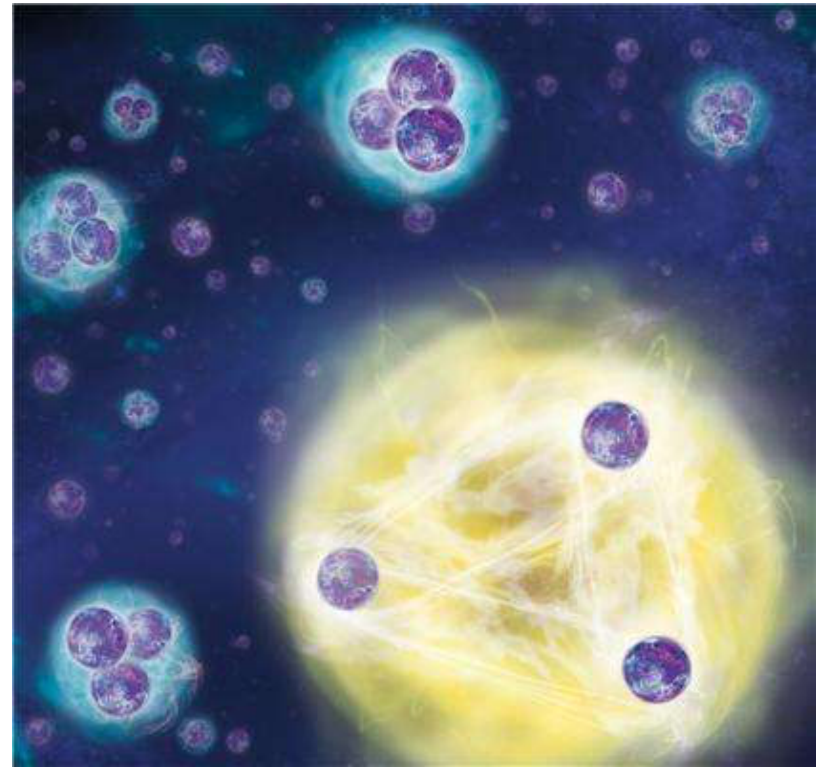
A. Tumino et al. PLB (2015) 59



Random coincidences for both spectra are shown as green dots. Their negligible contribution to the peaks is consistent with the interpretation of triple α correlation.

Can we link this correlation with the Efimov mechanism?

Efimov idea: A system of three particles with resonant two-body interactions may form bound states, the so called Efimov trimers, even when any two of the particles are unable to bind.



No observation exists yet in nuclei

Efimov has predicted the possibility of existence of trimers in a system of three α-particles, with a maximum radius of attraction of the order of the Bohr radius, $a_C = 1/e^2$, due to the repulsive long-range Coulomb potential.

His prescription refers mainly to ^{12}C levels in the vicinity of the threshold of breakup into three α-particles or α + ^{8}Be, and here we are much higher with the excitation energy.

Other interpratation

^{6}Li+α+*d* *Efimov* trimer in the entrance channel (zero energy). Thus, systems with correlated a particles can be seen as escape channels from Efimov.

Clustering in light nuclei: do they play a role in the sub-Coulomb fusion processes?

From the α_3 spectrum: the bulk of recombination into 3α particles pertains to the 90° region. First reason: contribution of the 22.2 MeV level of ^{8}Be.

Side reason: α_3 around 90° corresponds to 3α particles in a line and can be linked to two interacting ^{6}Li in a stretched α–d–d–α configuration that corresponds to the minimum value of the Coulomb barrier.

Next step: To investigate the role of clustering in the sub-Coulomb fusion processes of light nuclei with pronounced cluster structure, we have started with the ^{6}Li + ^{6}Li→3α reaction (Q = 20.9 MeV). The aim is to investigate the decrease of its cross section while decreasing the interaction energy from above to below the Coulomb barrier. If clustering plays a role, the system should experience a lower decrease of the cross section than expected.

Conjecture for nuclear astrophysics: there might be the possibility that other direct processes never considered at sub-Coulomb energies, triggered by the cluster structures of the interacting nuclei that manage to reduce the overall Coulomb barrier, may contribute to unsolved problems…

Conclusions

Many years ago the idea that atomic nucleus might show a cluster substructure has stronly supported the development of the physics of clusters, revealing a wide variety of clustering ranging from nuclear molecules to possible chains of a-particles.

This physics is still very attractive and lends itself to many applications:

- Nuclear astrophysics and the THM: virtual projectile/targets to overcome the main issues of nuclear reactions at astrophysical energies

- Strong correlations and a conglomerates possibly connected with the Efimov mechanism in nuclei → still a lot to understand

- Role of clustering in the sub-Coulomb fusion processes of light nuclei with pronounced cluster structure

To be continued …

THANK YOU!