Nuclear Spectroscopy with the TTT3 tandem accelerator in Naples

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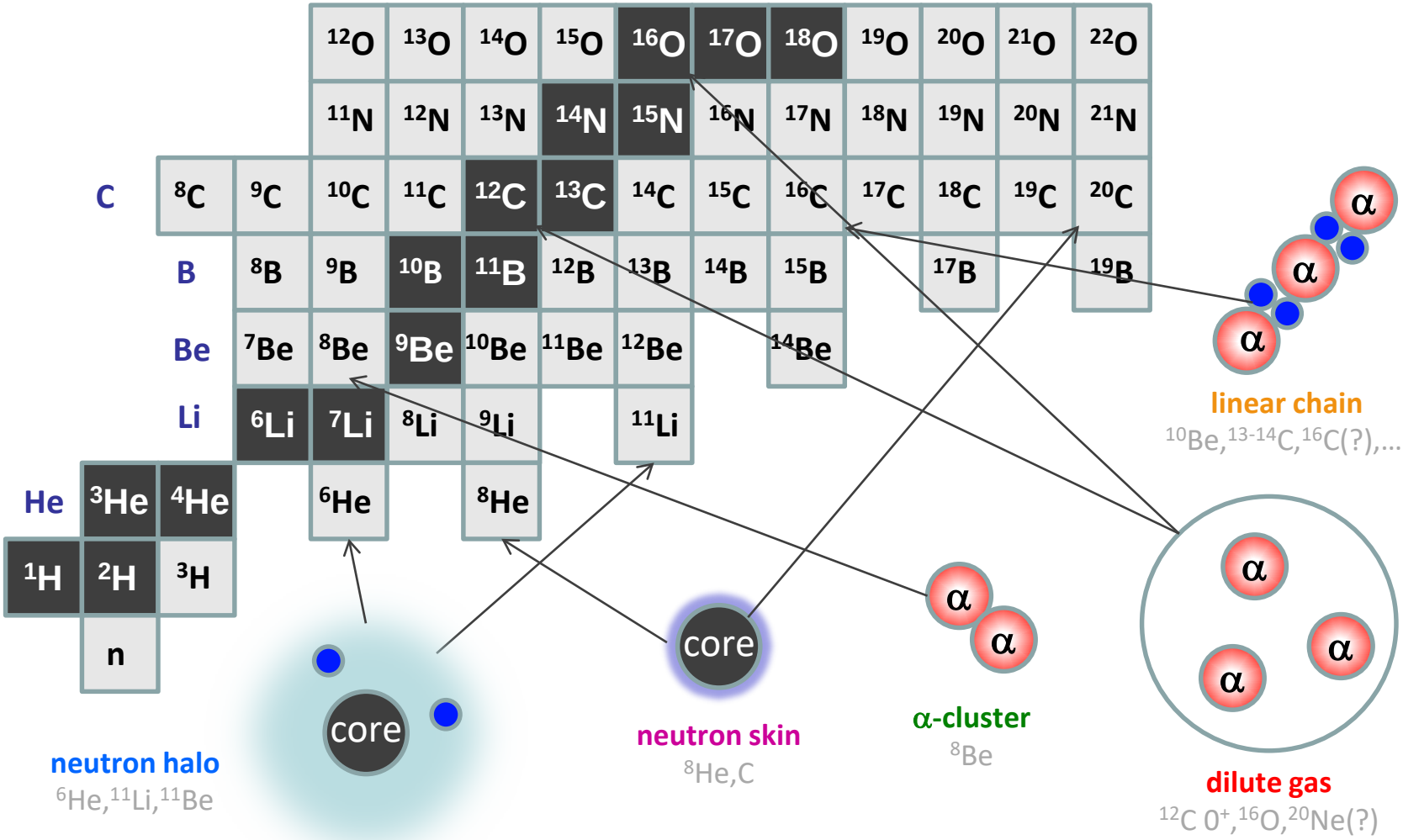
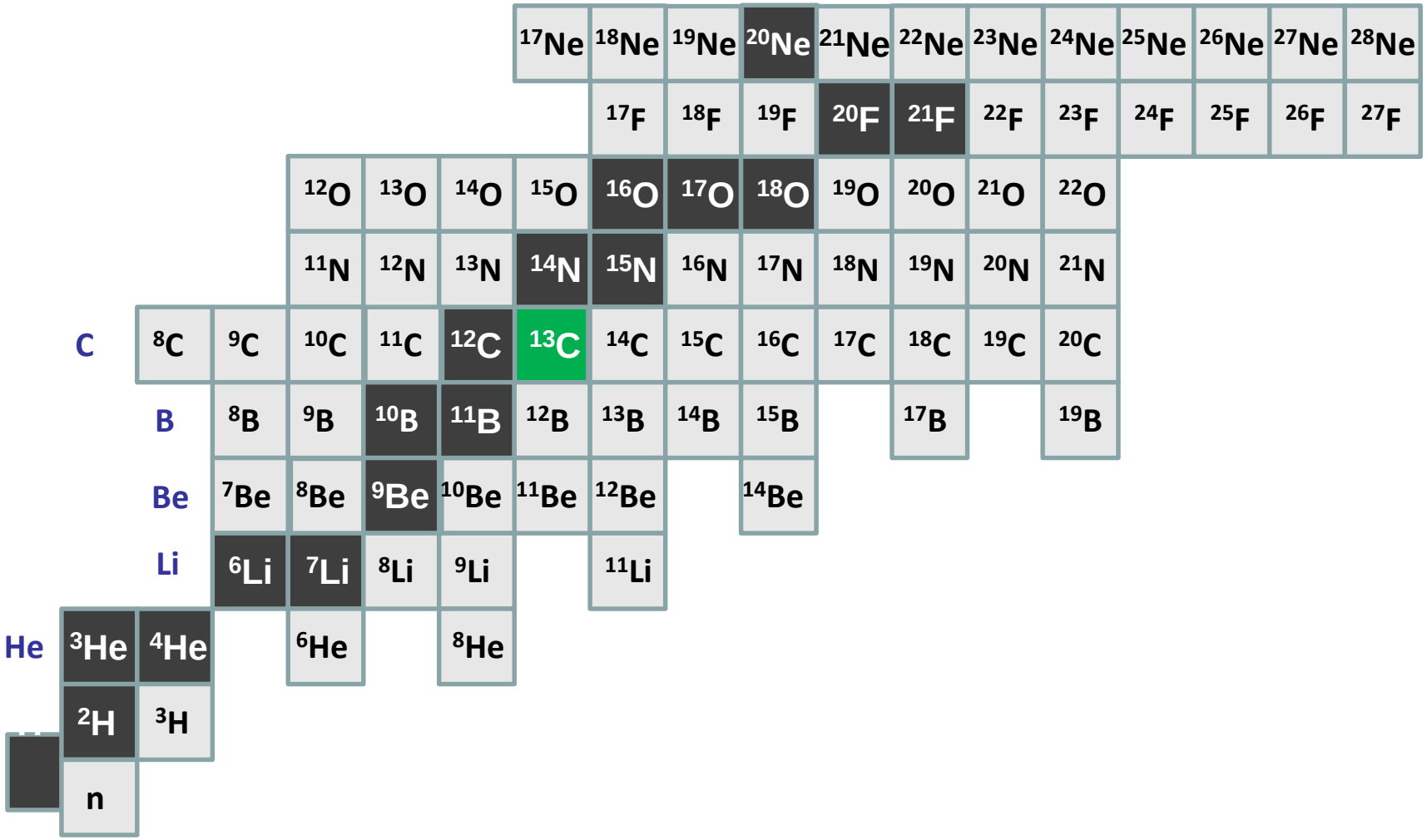
Complexity of nuclear force → deviation from the ***sphericity***: axial deformation (collective behaviours), spatial re-organization of nucleons in bounded **sub-units** (***cluster model***).

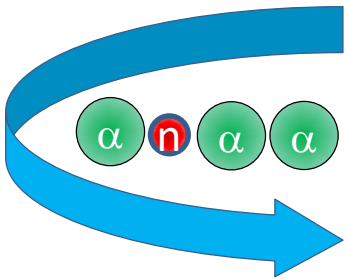


Nuclear Spectroscopy of light systems: an *experimental* campaign at the TTT3 tandem accelerator

Clustering in ^{13}C with α + ^{9}Be reactions

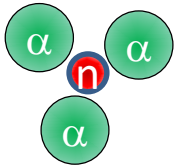


^{13}C structure via the ^{9}Be(α,α) EBS: R-matrix calculations



rotating deformed structures → rotational bands.

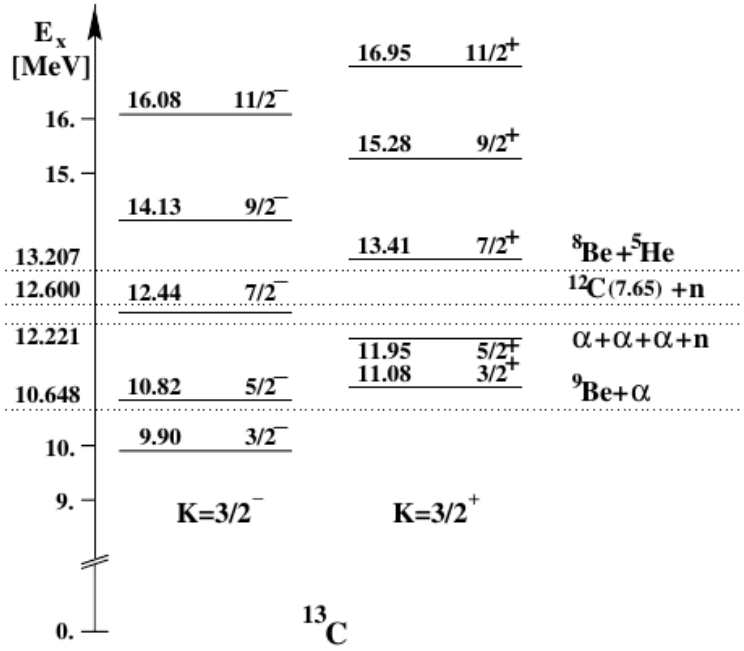
prolate (nuclear chain structure)



oblate (possible 3α+n Hoyle analog state in 13C)

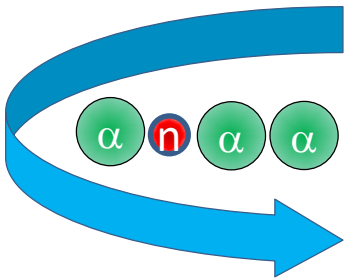
Near and above the α-threshold →different α-cluster configurations proposed for ^{13}C →theoretical works:

M. Milin and W. Von Oertzen EPJ A **14** (2002) 295
proposed parity doublet band of $^{9}Be_{gs}$ + α cluster prolate configuration → J^{π} assigments based on the rotational bands ($K=3/2^{\pm}$).



M. Milin and W. Von Oertzen EPJ A **14** (2002) 295

^{13}C structure via the ^{9}Be(α,α) EBS: R-matrix calculations



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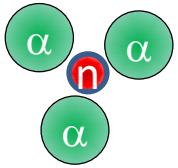

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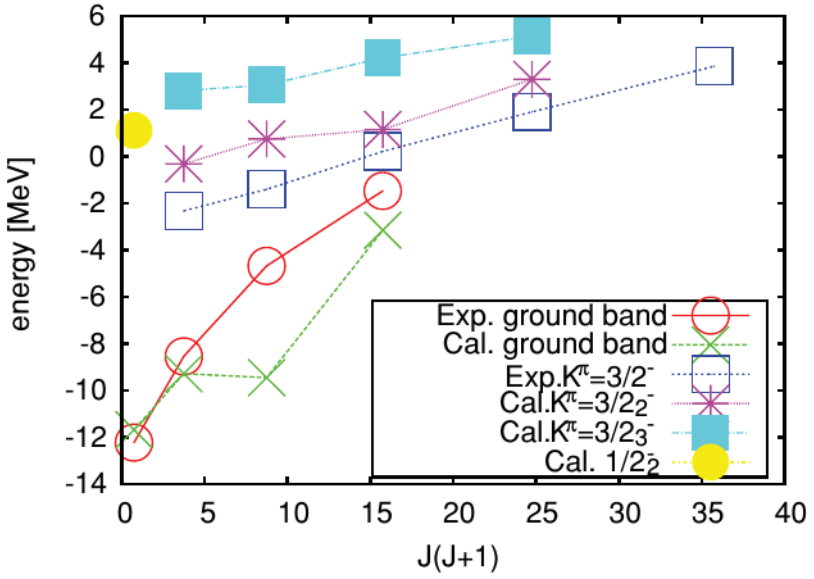
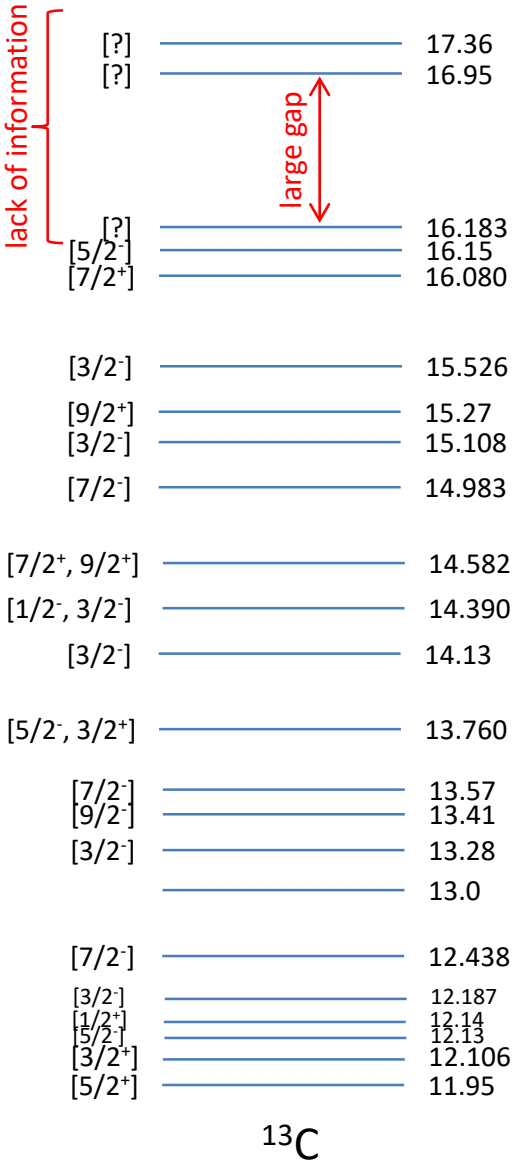
T. Yoshida, N. Itagaki and T. Otsura, Phys. Rev. C 79 (2009)

N. Furutachi and M. Kimura, Phys. Rev. C 83 (2011)
microscopic 3α+n model → proposed two new rotational bands ($K=3/2^{-}_{2}$ and $K=3/2^{-}_{3}$).

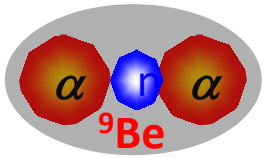


N. Furutachi and M. Kimura, Phys. Rev. C 83 (2011)



from Ajzemberg-Selove compilation

To investigate the structure of ^{13}C above the α-threshold (10.651 MeV) → $^{9}Be(\alpha,n)$, $^{9}Be(^{6}Li,d)$,$^{13}C(\alpha,\alpha')$, $^{9}Be(\alpha,\alpha)$ etc.



The ***Resonant Elastic Scattering*** is particularly suited for investigating states in the compound ^{13}C with α-cluster nature since the **^{9}Be** presents a well developed ***molecular nature***.

• R.B. Taylor et al, NPA 65 (1965) 318	DK	$6.3 < E_{lab} < 19.7$
• J.D. Goss et al, PRC 7 (1973)	DK	$1.7 < E_{lab} < 5.6$
• Z.A. Saleh et al, Ann. Phys. 7 (1974) 76	DK	$1.4 < E_{lab} < 2.5$
• J. Leavitt et al, NIM B 85 (1994) 37	DK	$0.6 < E_{lab} < 4.2$
• J. Liu et al, NIM B 108 (1996) 247	DK	$0.9 < E_{lab} < 5.3$
• M. Zadro et al, NIM B 259 (2007) 836	IK	$2.0 < E_{cm} < 4.3$
• M. Freer et al, PRC 84 (2011) 034317	IK	$1.6 < E_{cm} < 6.0$
• I. Lombardo et al, NIM B 302 (2013) 19	DK	$2.4 < E_{cm} < 6.4$

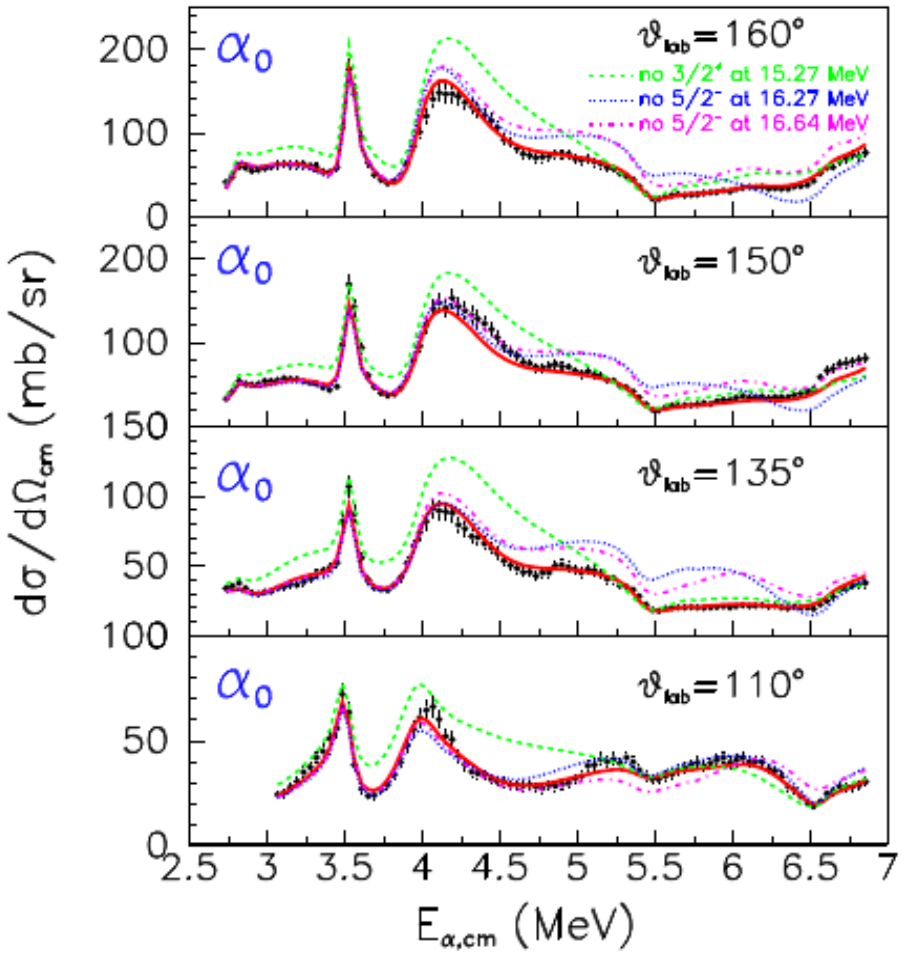
New measurement at the Naples TTT3 accelerator!

^{4}He beam: E_{max}=10 MeV!!!

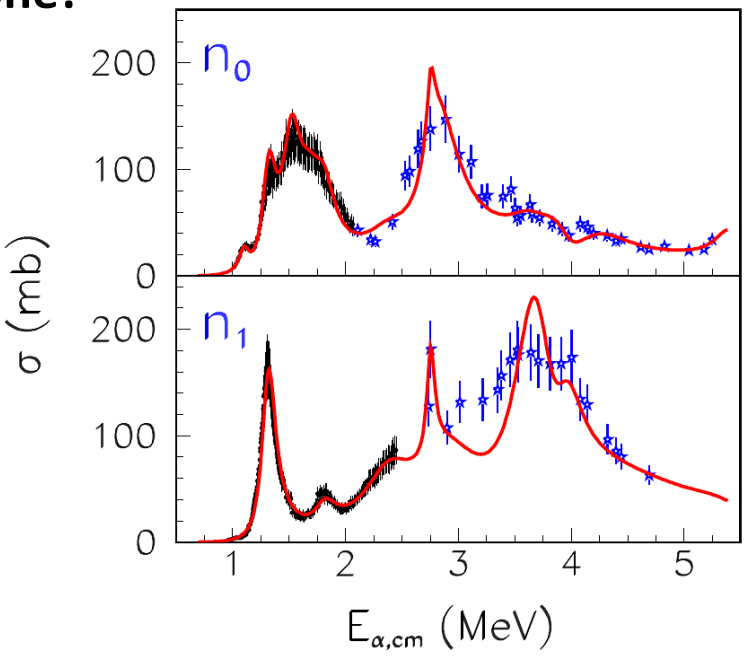
V_t = 3.33 MV, larger than the *maximum* one!

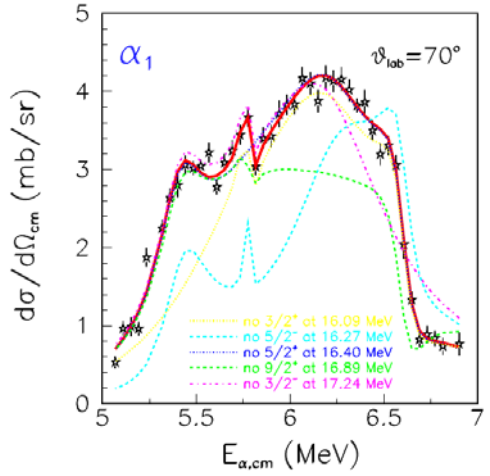
Useful for IBA → Be in samples!

^{9}Be(α,α$_0$)



^{9}Be(α,n$_0$,n$_1$)





^{9}Be(α,α$_1$)

L. van der Zwan and K.W. Geiger, Nucl. Phys. A 152 (1970) 481

literature		our data from the TTT3 exp.					
E_x^{lit}	J^{π}_{lit}	E_x	J^{π}	Γ	Γ_{α_0}	Γ_{α_1}	Γ_n
11.75	$3/2^-$	11.75	$3/2^-$	116	3	-	113
11.97	$5/2^+$	11.97	$5/2^+$	152	65	-	87
12.13	$5/2^-$	12.17	$5/2^-$	199	28	-	171
12.14	$1/2^+$	12.33	$1/2^+$	230	40	-	190
12.44	$7/2^-$	12.45	$7/2^-$	222	16	-	206
13.28	$3/2^-$	13.05	$3/2^-$	546	153	-	393
13.41	$9/2^-$	13.41	$9/2^-$	84	21	-	63
13.57	$7/2^-$	13.49	$7/2^-$	417	114	-	303
13.76	$(3/2,5/2)^+$	13.63	$5/2^+$	743	623	-	120
14.13	$3/2^-$	14.13	$5/2^-$	94	94	-	-
		14.17	$7/2^+$	6	6	-	-
14.39	$(1/2,5/2)^-$	14.27	$7/2^-$	392	185	-	207
14.58	$(7/2,9/2)^+$	14.36	$9/2^+$	322	70	-	252
14.63		14.64	$7/2^-$	361	279	-	82
14.98	$(7/2^-)$	15.04	$5/2^+$	964	830	-	134
15.27	$9/2^+$	15.27	$3/2^+$	1201	1061	-	140
16.08	$(7/2^+)$	16.09	$3/2^+$	365	233	55	77
		16.27	$5/2^-$	1596	1503	87	6
		16.40	$5/2^+$	17	2	14	1
		16.64	$5/2^-$	1501	1294	10	152
		16.67	$7/2^+$	904	633	2	-
16.95		16.89	$9/2^+$	635	501	86	4
		16.91	$3/2^-$	1080	703	257	120
		17.23	$3/2^+$	393	280	-	113
17.36		17.24	$3/2^-$	215	184	20	11
		17.52	$5/2^+$	2153	1834	86	233
17.92		17.86	$7/2^-$	477	457	-	20

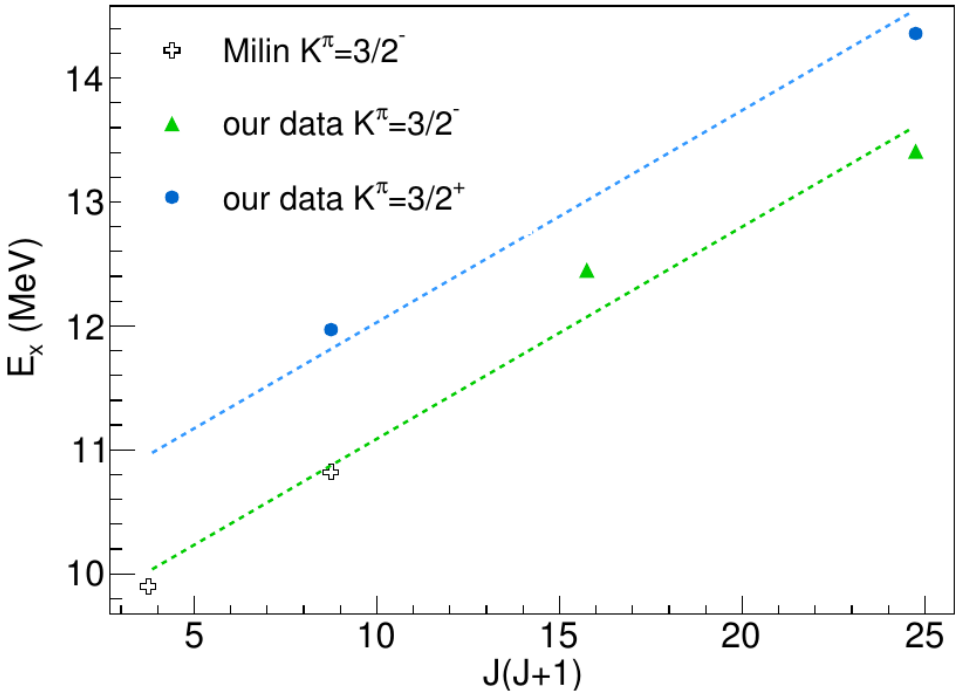
New ^{13}C spectroscopic information in a very wide energy range.

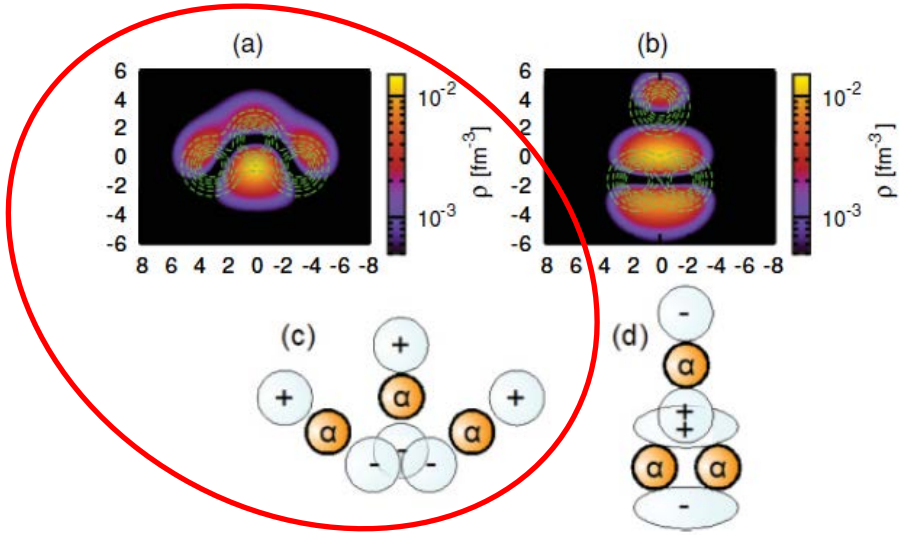
Improved spin/parity assigments thanks to the *simultaneous fit* of several angles and channels.

Excellent opportunity given by the ***TTT3 accelerator*** to study the α+^{9}Be reaction with ***more than 150*** energy changes!!!

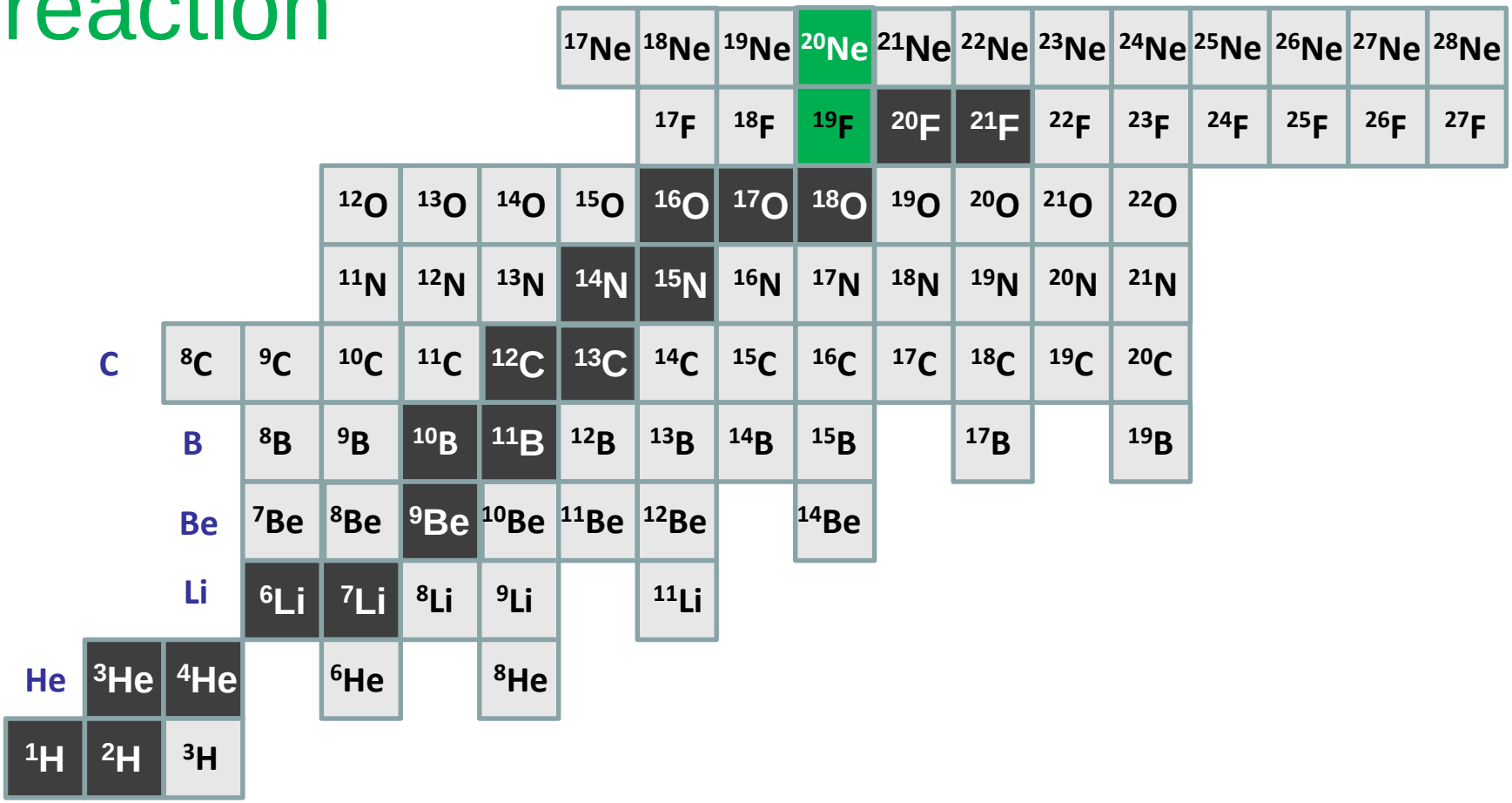
Some **results:**

- ***2 opposite parity*** ***group of*** **states could match the rule of** ***rotational band*****;**
- ***Large separation*** **between the two opposite parity bands (≈1 MeV);**
- **Almost** ***parallel*** **bands;**
- ***Short bands*****: centrifugal stress?**
- ***Very large*** **values of** ***moment of inertia*****: similar to the ones calculated with the GCM by Kimura & Furutachi**

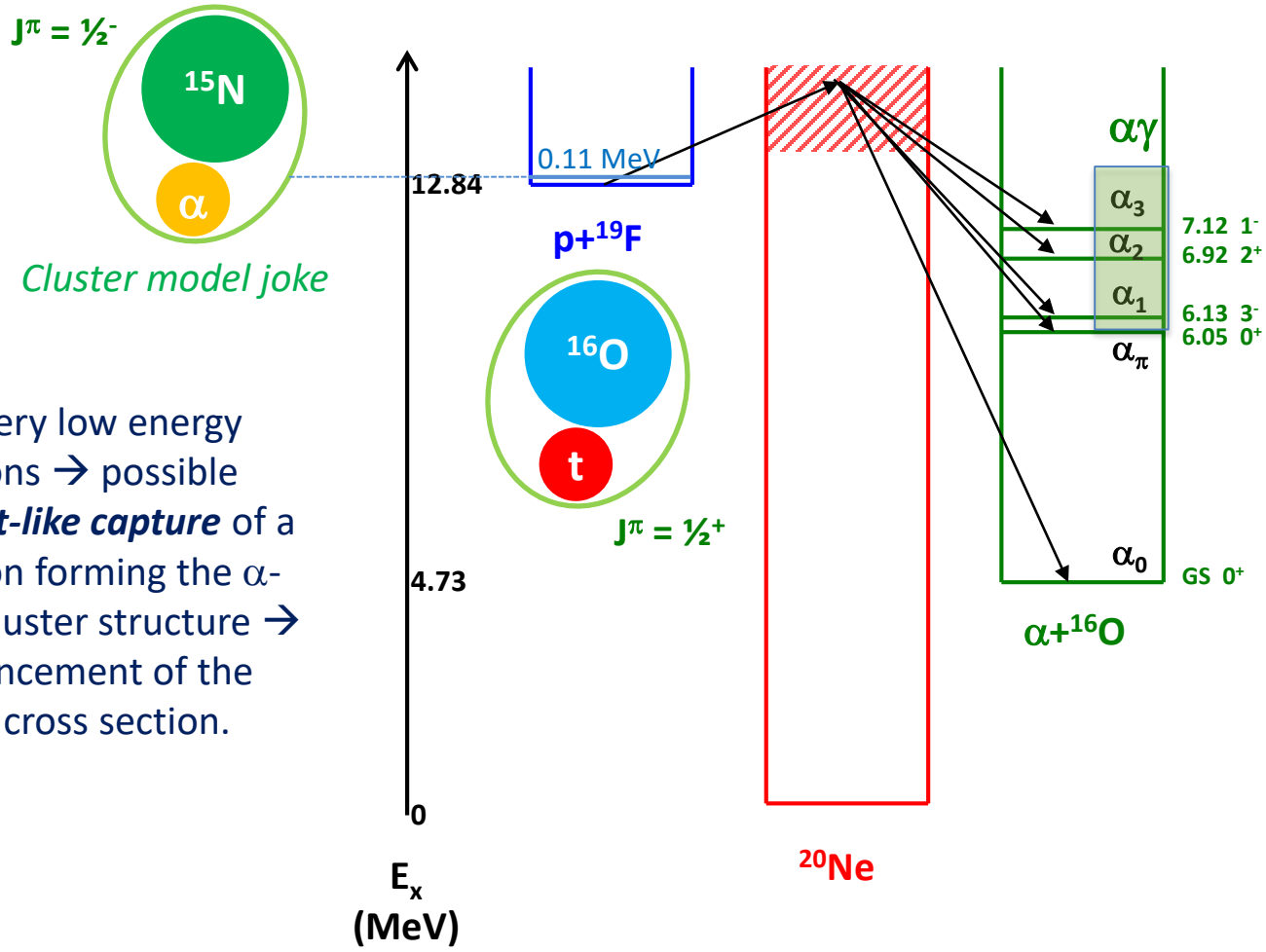




Cluster structures in ^{20}Ne and ^{19}F and their role in the ^{19}F(p,α)^{16}O reaction



$^{19}F(p,\alpha_0)$ and $^{19}F(p,\alpha_\pi)$ at ***sub-barrier energies*** → ***quartet states*** [1,2] in ^{20}Ne

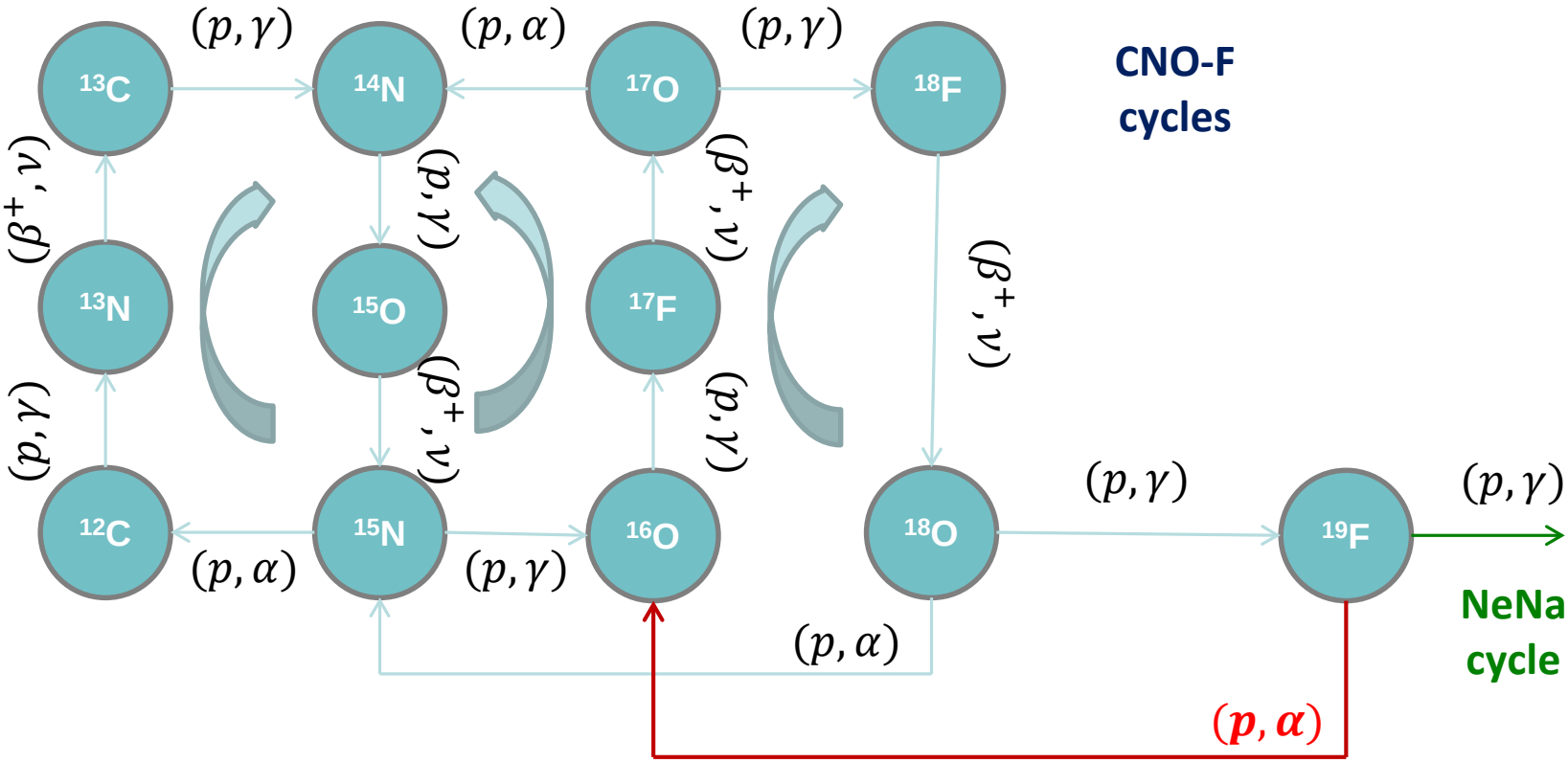


For very low energy protons → possible ***direct-like capture*** of a proton forming the α-^{16}O cluster structure → enhancement of the (p,α) cross section.

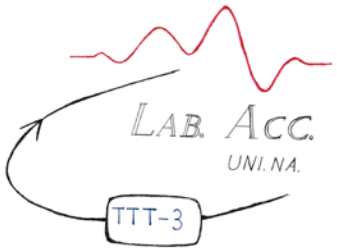
[1] M. Danos and V. Gillet, *Phys. Rev.* 161 (1967) 1034
[2] A. Arima, V. Gillet and J. Ginocchio, *Phys. Rev. Lett.* 25 (1970) 1043
[3] P. Cuzzocrea, A. De Rosa, G. Inglima, E. Perillo, E. Rosato, M. Sandoli and G. Spadaccini, *Lett. Nuov. Cimento* 28 (1980) 515.
[4] R. Caracciolo, P. Cuzzocrea, A. De Rosa, G. Inglima, E. Perillo, M. Sandoli and G. Spadaccini, *Lett. Nuov. Cimento* 11 (1974) 33.

$^{19}F(p,\alpha_0)$ and **$^{19}F(p,\alpha_\pi)$** at ***sub-barrier energies*** → ***quartet states*** **[1,2]** in **^{20}Ne** → ***Ambiguities*** **in ^{20}Ne** ***spectroscopy*** **above the S_p (12.844 MeV) [3]**

S(E) factor low energy **extrapolation** → **astrophysical interest** → **CNOF cycles, fluorine *nucleosynthesys***



[1] M. Danos and V. Gillet, *Phys. Rev.* **161** (1967) 1034
[2] A. Arima, V. Gillet and J. Ginocchio, *Phys. Rev. Lett.* **25** (1970) 1043
[3] D.R. Tilley et al., *Nucl. Phys.* **A 636** (1998) 247



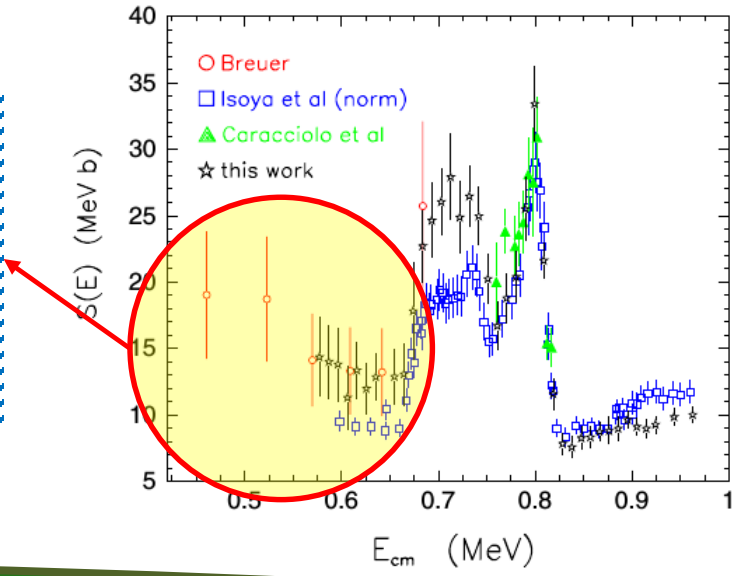
This time, at the *low energy* limits of the machine!
E_p=0.6-1.2 MeV

^{20}Ne *spectroscopy* vs Tilley et al. [1]

E_p (keV)	J^π (Ref. [1])	J^π
≈ 650	1^-	1^-
710	(1^-)	(1^-)
733	2^+	2^+
778	2^+	2^+
≈ 825		1^-
842	$(0^+, 2^+)$	0^+

Non resonant **S(E) → 40% *larger* than NACRE**
What is happening at 0.4 – 0.5 MeV?
Resonances → Trojan Horse Method

M. La Cognata et al., *Astro. J. Lett.* **739** (2011) L54



[1] D.R. Tilley et al., *Nucl. Phys.* **A 636** (1998) 247

Highlights of 2013 Journal of Physics G: Nuclear and Particle Physics

We've had some great work published in JPhysG too, and here we've picked out some of our research highlights from 2013. Each article comes highly commended from the journal's editors for the presentation of outstanding research, and congratulations go to each of the authors for their excellent work.

Nuclear and particle astrophysics

Hide article list

Effects of large extra dimensions on cosmogenic neutrino flux

M M Reynoso and O A Sampayo 2013 *J. Phys. G: Nucl. Part. Phys.*

+ View abstract View article PDF

Leptogenesis in models with keV sterile neutrino dark matter

F Bezrukov *et al* 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 095202

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Neutral- and charged-current supernova-neutrino scattering

W Almosly *et al* 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 095201

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The neutron background of the XENON100 dark matter searc

E Aprile *et al* 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 115201

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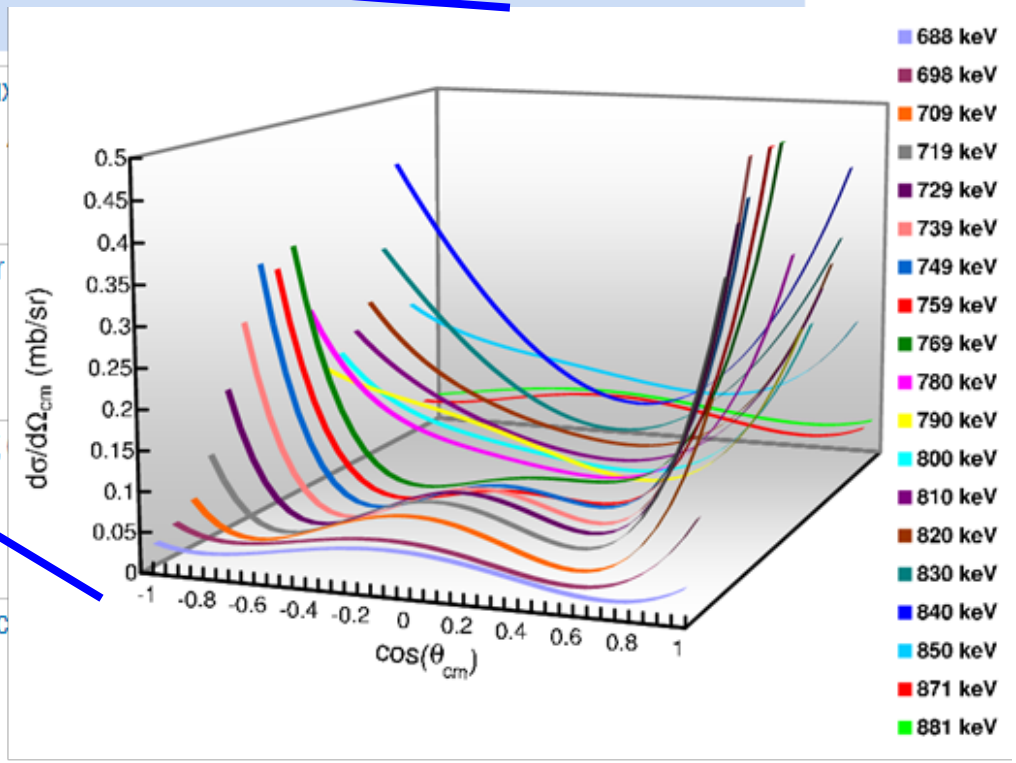
Read the LabTalk

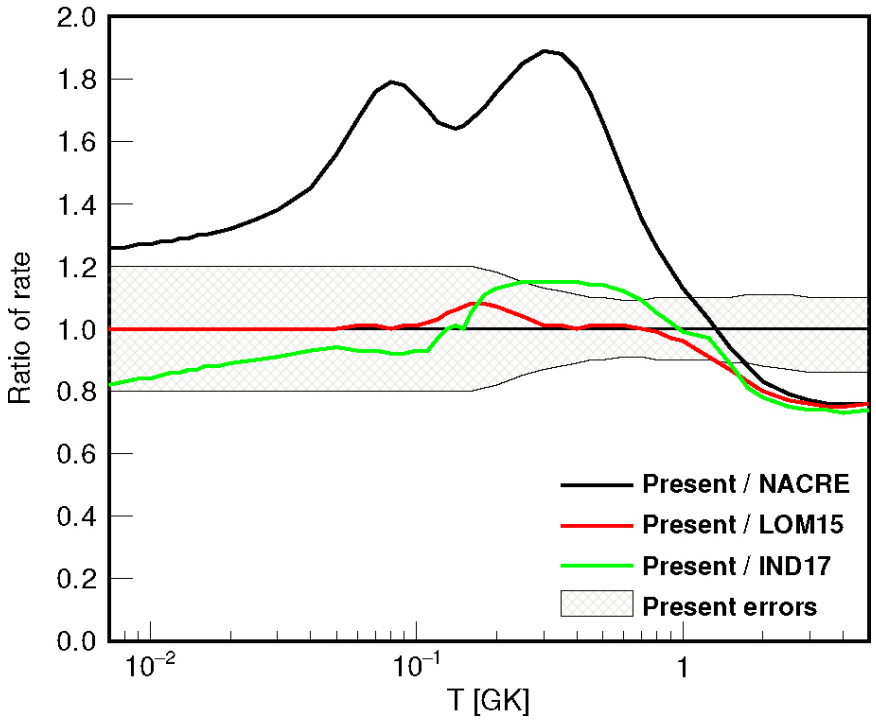
Analysis of the $^{19}F(p, \alpha_0)^{16}O$ reaction at low energies and the spectroscopy of ^{20}Ne

I Lombardo *et al* 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 125102

+ View abstract View article PDF



J.-J. He, I. Lombardo, D. Dell'Aquila, Y. Xu, L.-Y. Zhang and W.-P. Liu, Chin. Phys. C 42 (2018) 015001

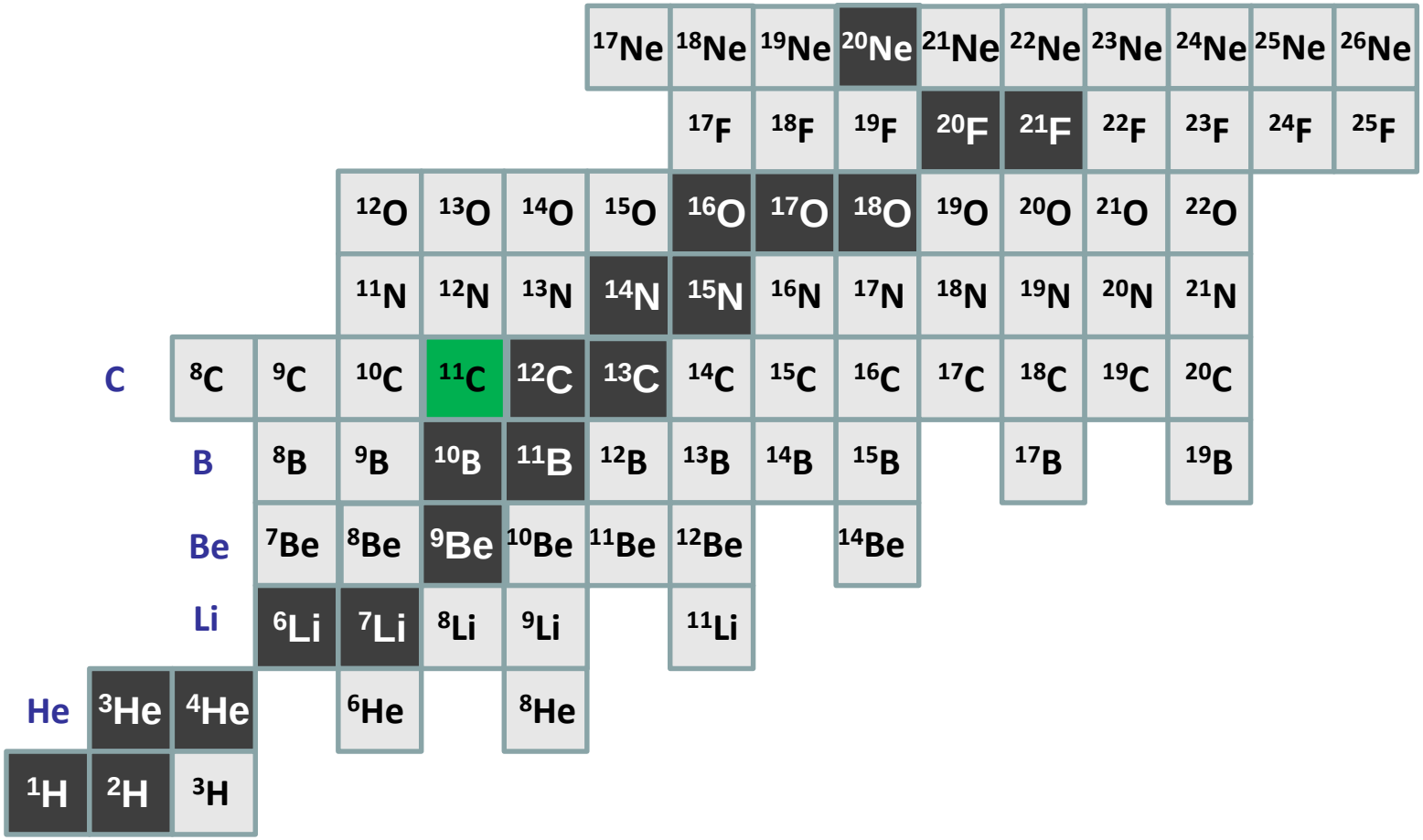


I. Indelicato et al., The Astrophysical Journal 845 (2017) 19 → confirming the role of the cluster state at 0.251 MeV via the THM method.

W.P. Liu et al., EPJ Web Conf. 109 (2016) 09001 → Jinping Underground laboratory for Nuclear Astrophysics (JUNA).

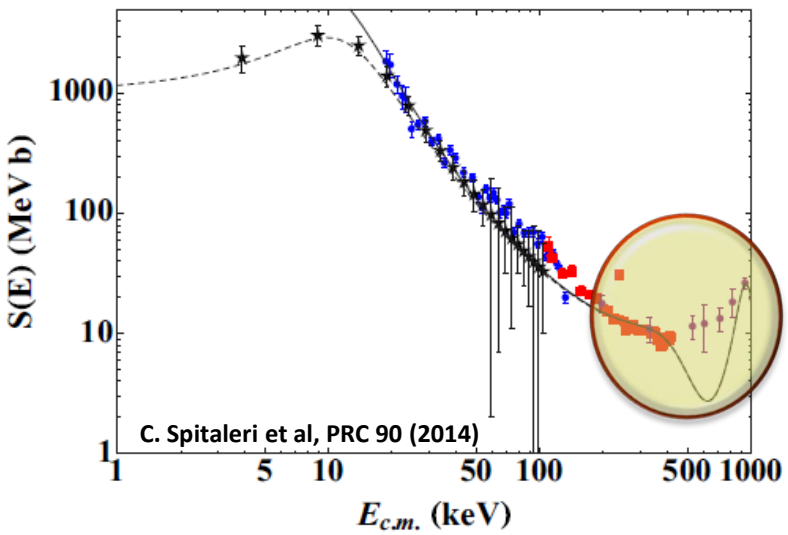
New collaboration with JUNA → exp. at very low energies (down to 80 keV)

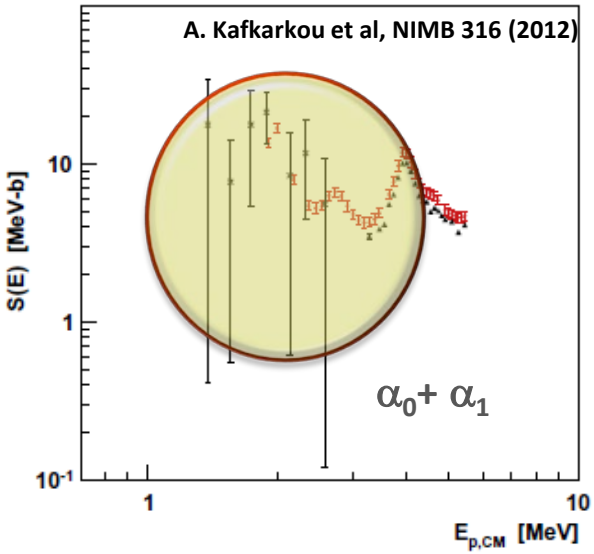
The structure of ^{11}C with the $^{10}B(p,\alpha)^{7}Be$ reaction



Importance of the ^{10}B(p,α) ^{7}Be reaction at *low energy*:

- *Structure* of the compound nucleus, ^{11}C (*clustering*, IAS …)
- *Astrophysical* importance → ^{10}B *destruction* in stars
- *Applied physics* context → *a-neutronic fusion*





- *Problems* in the description of the

  0.5 – 1.5 MeV region with *known states*

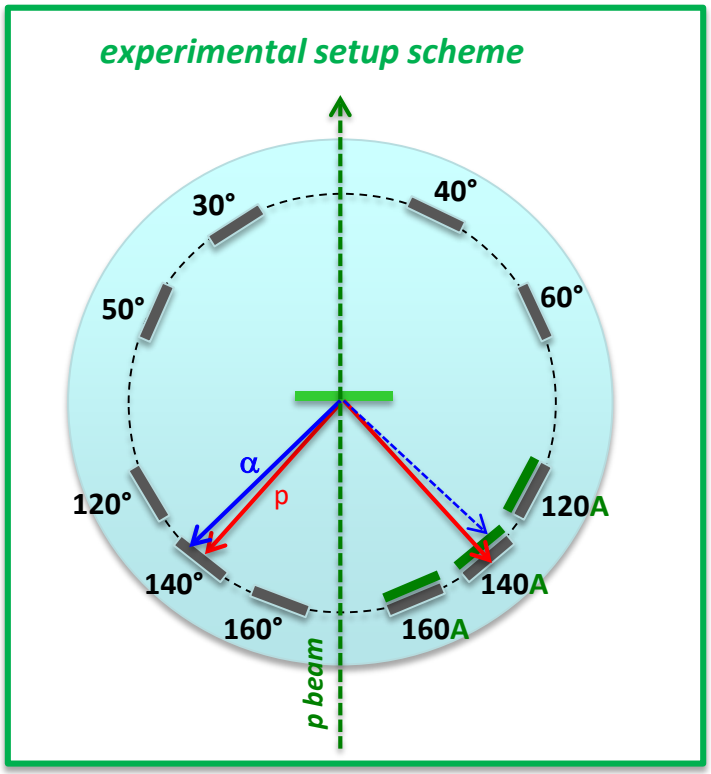
- Very *large error bars* from the (indirect) *thick target yield* measurement

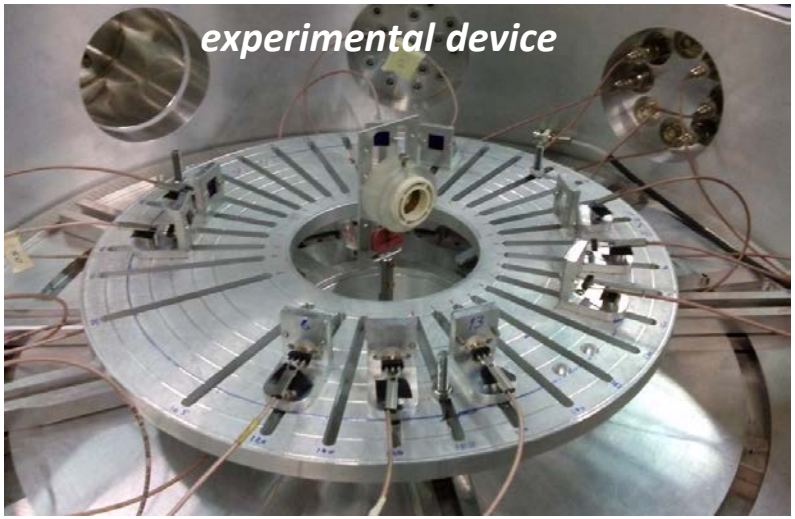
  [Roughton et al, ADNDT 23 (1979)]

Difficulties → kinematics & contaminants

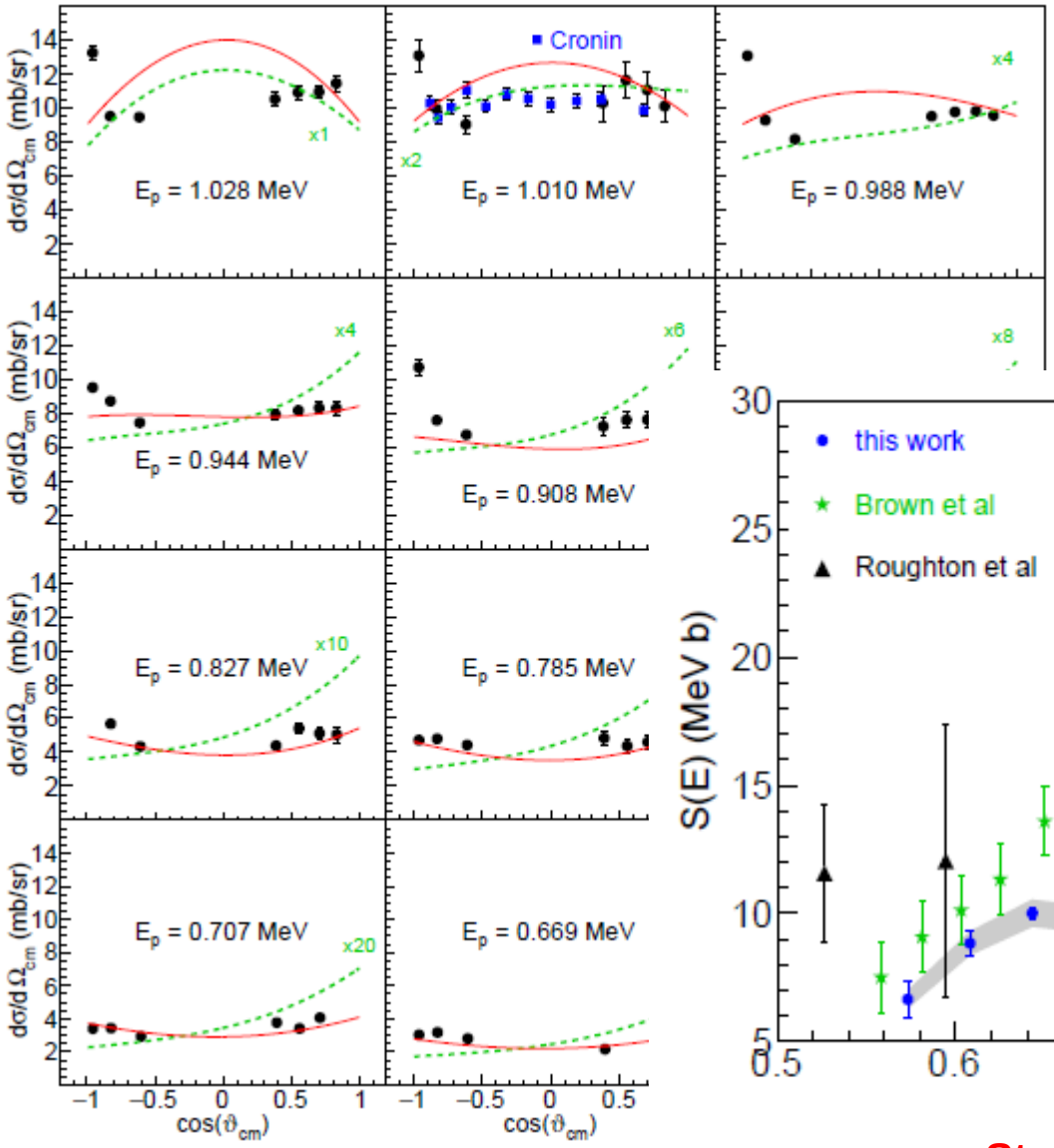
New experiment **in Naples with the TTT3 tandem: 0.6 – 1.1 MeV region:**

- **20 – 40 keV steps**
- **Self supporting ^{10}B target (40 μg/cm^2)**
  + formvar
- ***Forward*** **angles: 30, 40, 50, 60° → OK**
- ***Backward*** **angles (120, 140, 160°):**
  → ***inverse absorber*** **technique**
  (3 μm Al foil to highly degrade/stop α_0)



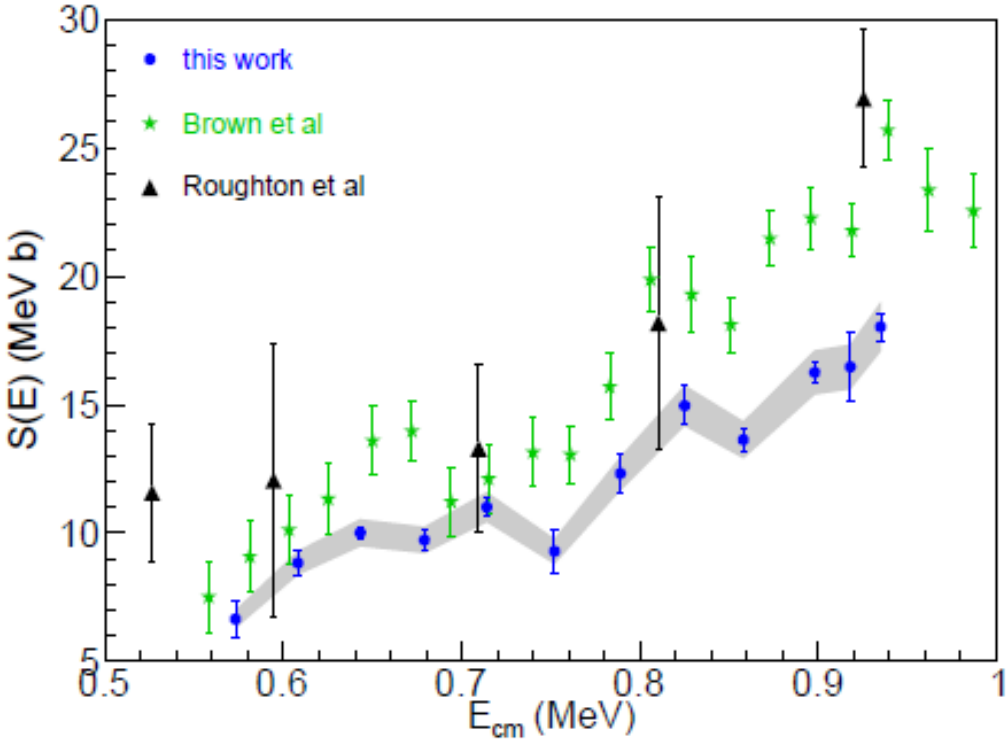


Angular distributions → slight ***deviations*** from isotropy → J^{π} of states in ^{11}C



--- ***R*-matrix** calculations with ***literature*** parameters

--- ***R*-matrix** calculations with ***new level parameters*** (***this work***, ***see later***)



States at E_x = 9 – 10 MeV in ^{11}C?

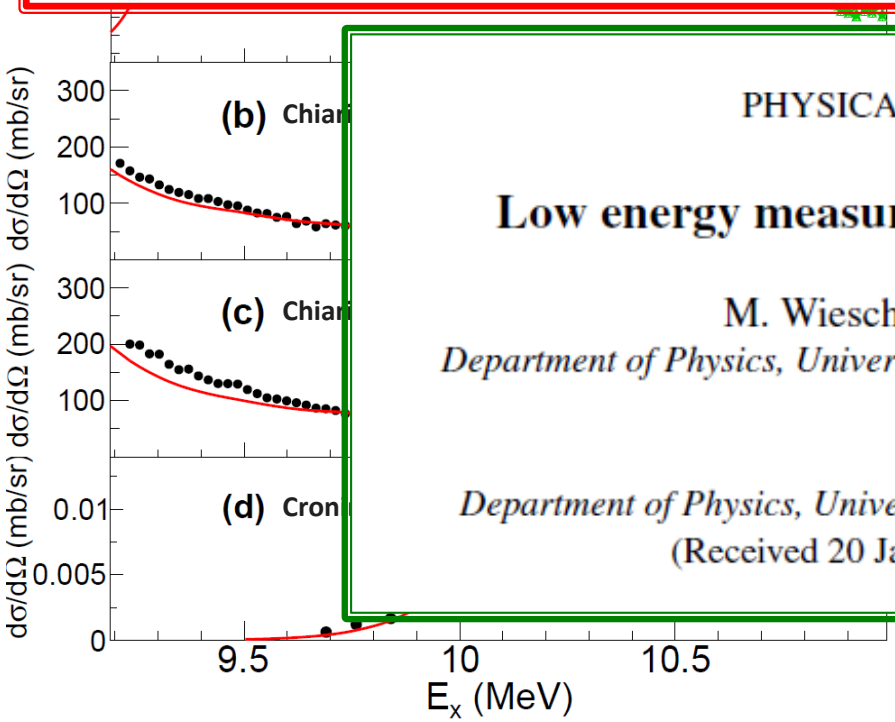
Eur. Phys. J. A (2016) **52**: 136
DOI 10.1140/epja/i2016-16136-8

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

A new study of ^{10}B(p, α)^{7}Be reaction at low energies

A. Caciolli[1,a], R. Depalo[1], C. Broggini[2], M. La Cognata[3], L. Lamia[4], R. Menegazzo[2], L. Mou[5], S.M.R. Puglia[3], V. Rigato[5], S. Romano[3,4], C. Rossi Alvarez[5], M.L. Sergi[3], C. Spitaleri[3,4], and A. Tumino[3,6]



PHYSICAL REVIEW C **95**, 044617 (2017)

Low energy measurements of the ^{10}B(p,α)^{7}Be reaction

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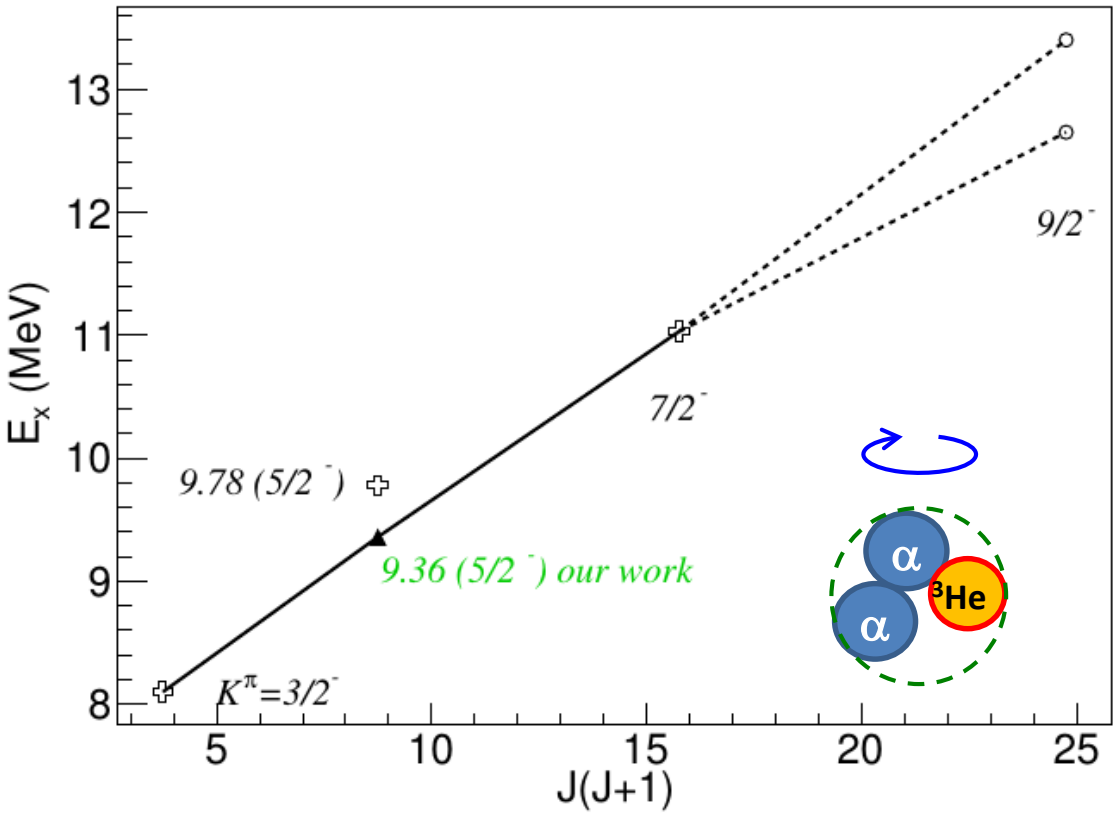
(Received 20 January 2017; published 26 April 2017)

States confirmed by Caciolli et al and Wiescher et al works



H. Yamaguchi et al. ,Phys. Rev. C 87 (2013) 034303
$K^\pi = 3/2^-$ rotational band (open symbols)

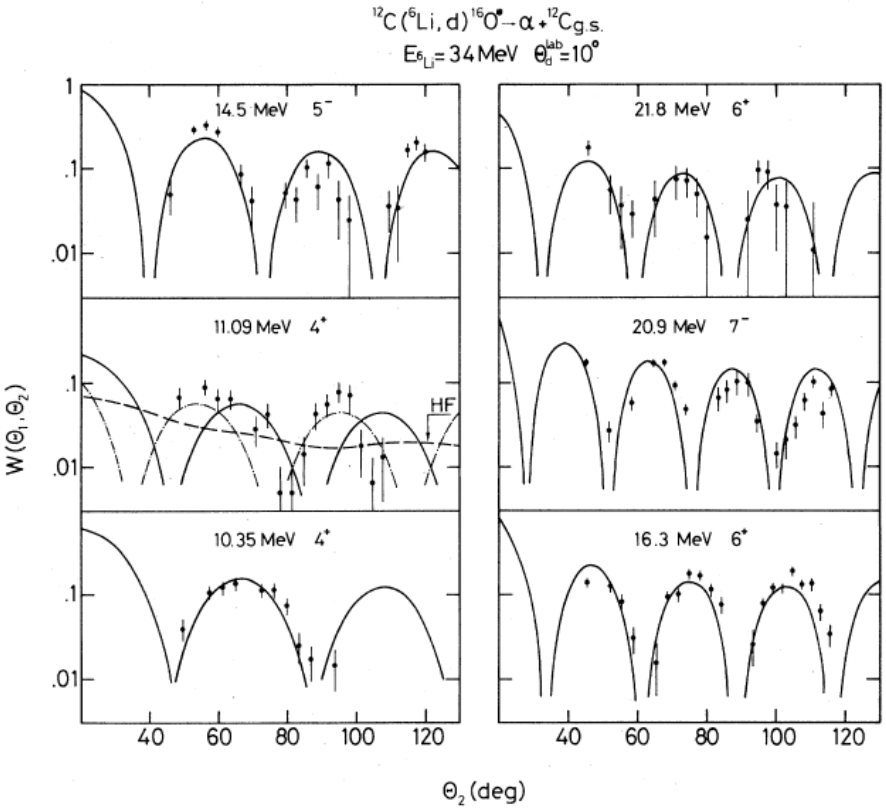
Rotational band $K^\pi = 3/2^-$ built on the 8.10 MeV state→ ambiguity in the assignment of the $9/2^-$ member ($\approx$ 13 MeV) → best fit with our 9.36 MeV $5/2^-$.

Transfer Reactions

(june 2015)

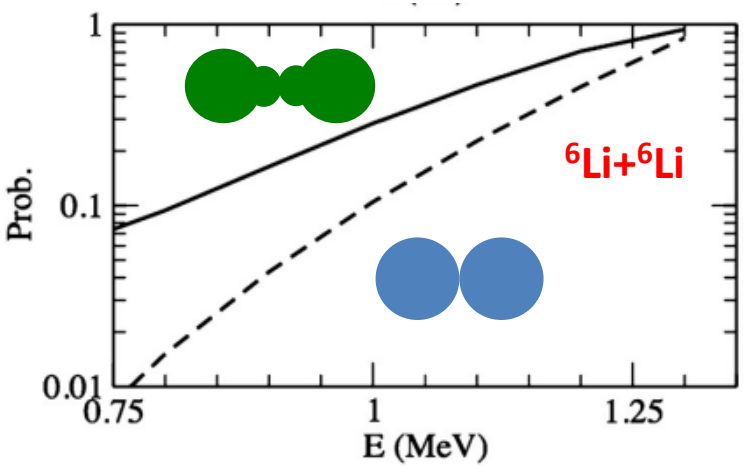
Alpha-transfer **reactions induced by ^{6,7}Li → a fundamental tool for studying states formed in** ***production experiments*** **and having large α-cluster structure**

Pioneering **studies by** ***Catania group*** **(G. Pappalardo, A. Cunsolo, G. Raciti et al) at the FN tandem of Saclay → the coupling of AD and AC allows to fix the J^π of excited,** ***particle-unbound*** **states.**



A. Cunsolo et al, Phys. Rev. C 21 (1980) 2345

With ***low energy Li beams*** **→ alpha-transfer reactions are highly sensitive to the** ***cluster structure*** **of proj. and target→ effects on** ***fusion cross section*****!**

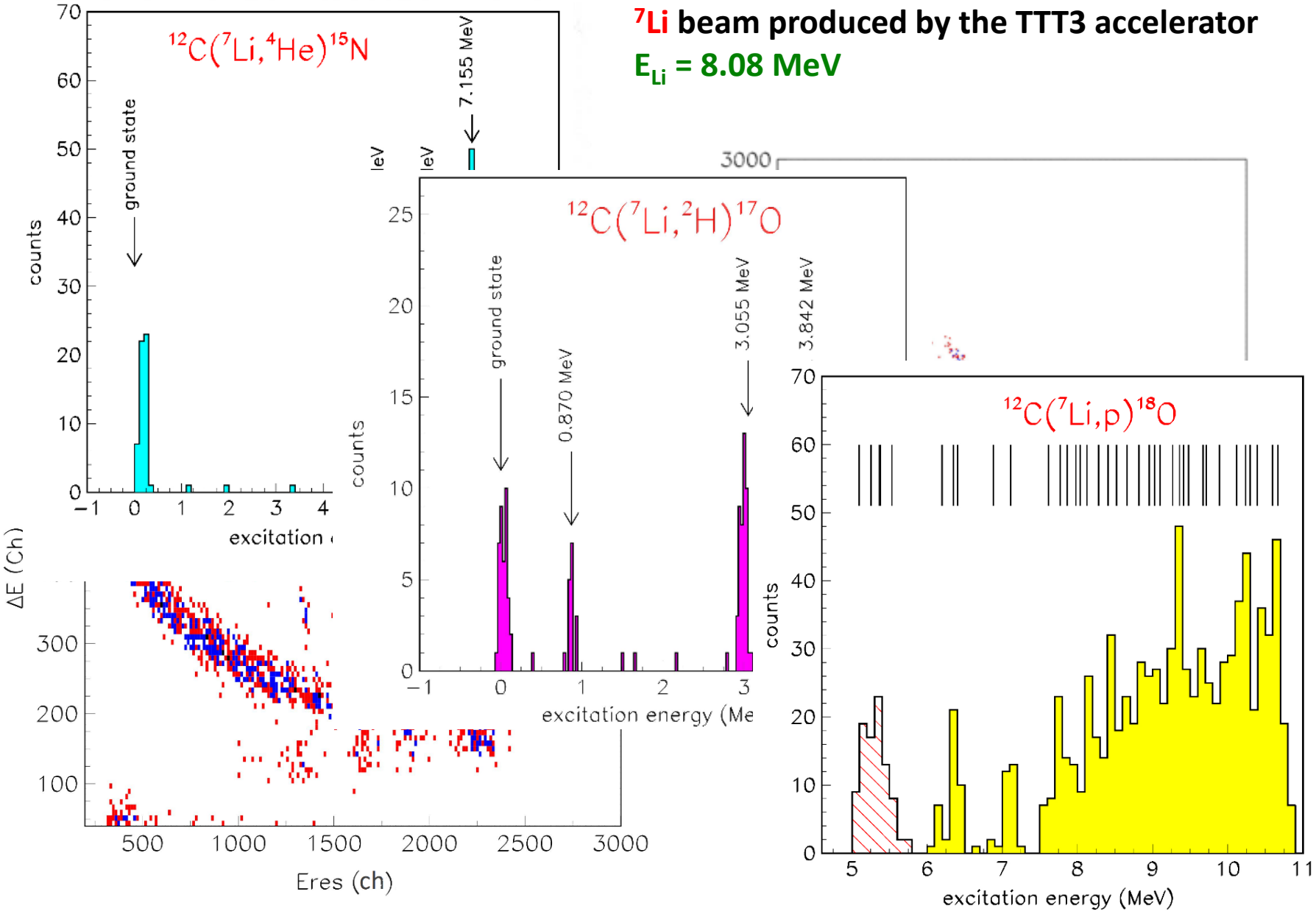


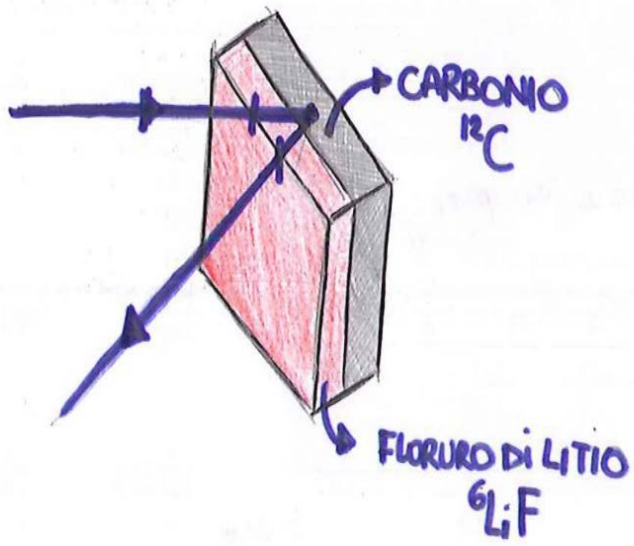
C. Spitaleri et al, Phys. Lett. B 755 (2016) 275

Importance of ^{6,7}Li beams at low energies!

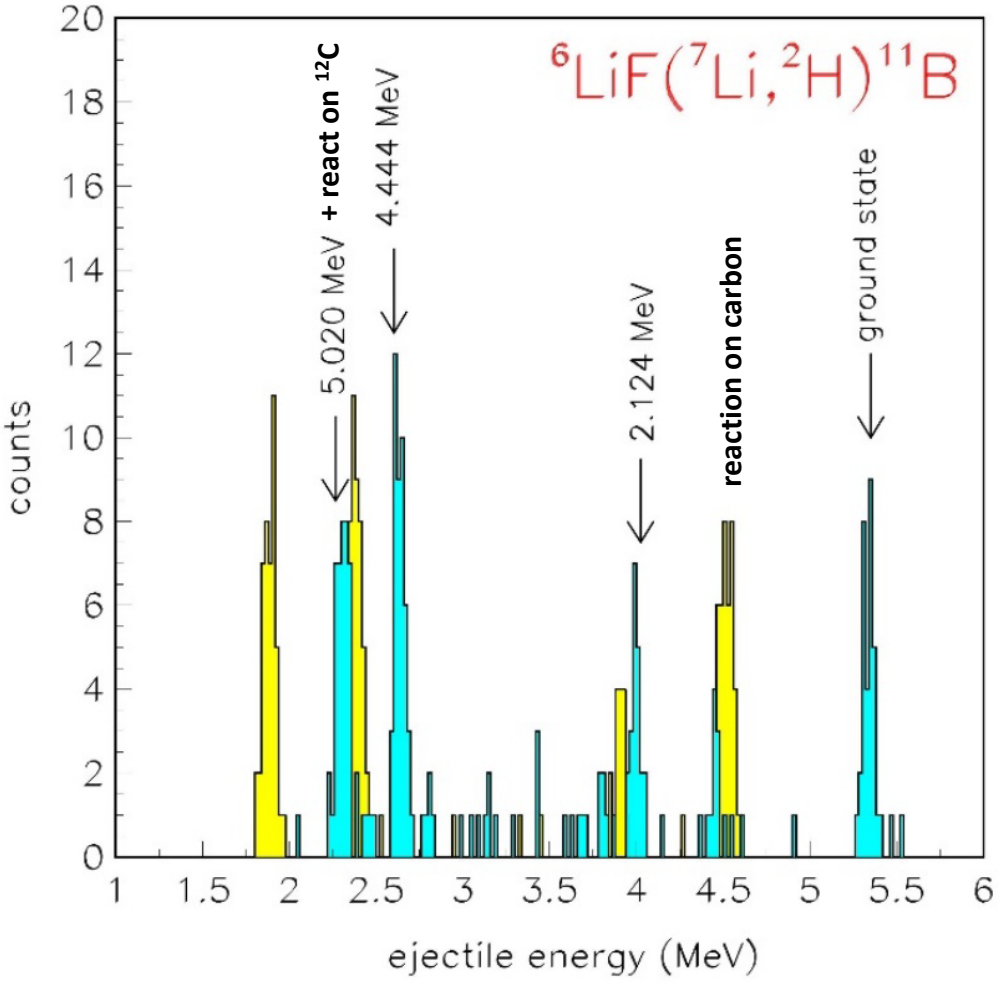
^{7}Li beam produced by the TTT3 accelerator

E_{Li} = 8.08 MeV





Reaction at the *same energy*, but on a compound target containing ^{6}Li



High resolution of *beam* and *detectors* → good evaluation of effects due to *contaminants*

The TTT3 tandem accelerator in Naples → *range* of beams (including the *precious* alpha ones), energy domain, energy resolution and quality of beams that make it an *excellent facility* for nuclear structure studies → alpha cluster model of light nuclei.

The *campaign* of experiment conduced by our group led to:

6 articles (+4 strictly related to our findings)

I. Lombardo, D. Dell'Aquila et al, J. Phys. G 40 (2013)

I. Lombardo, D. Dell'Aquila et al, J. Phys. G 43 (2016)

I. Lombardo et al, Nucl. Instrum. Meth. B (2013)

I. Lombardo et al, Acta Phys. Pol. B (2017)

I. Lombardo, D. Dell'Aquila et al, Phys. Rev. C *submitted*

J.J. He, I. Lombardo et al, Chin. Phys. C (2018)

≈ 20 conference proceedings

6 invited talks

1 Ph.D. thesis & 4 degree thesis

1 highlighted article