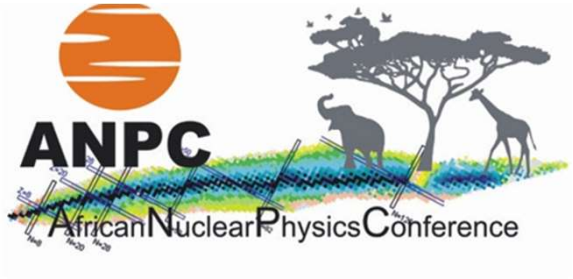
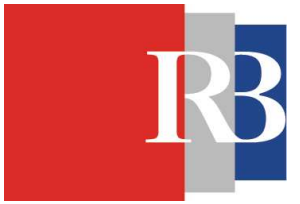


ANPC 2019,
Kruger National Park, RSA

Helium Decays of Excited States and Clustering in ^{17,18}O

Neven Soić
Ruđer Bošković Institute Zagreb, Croatia



Collaborators

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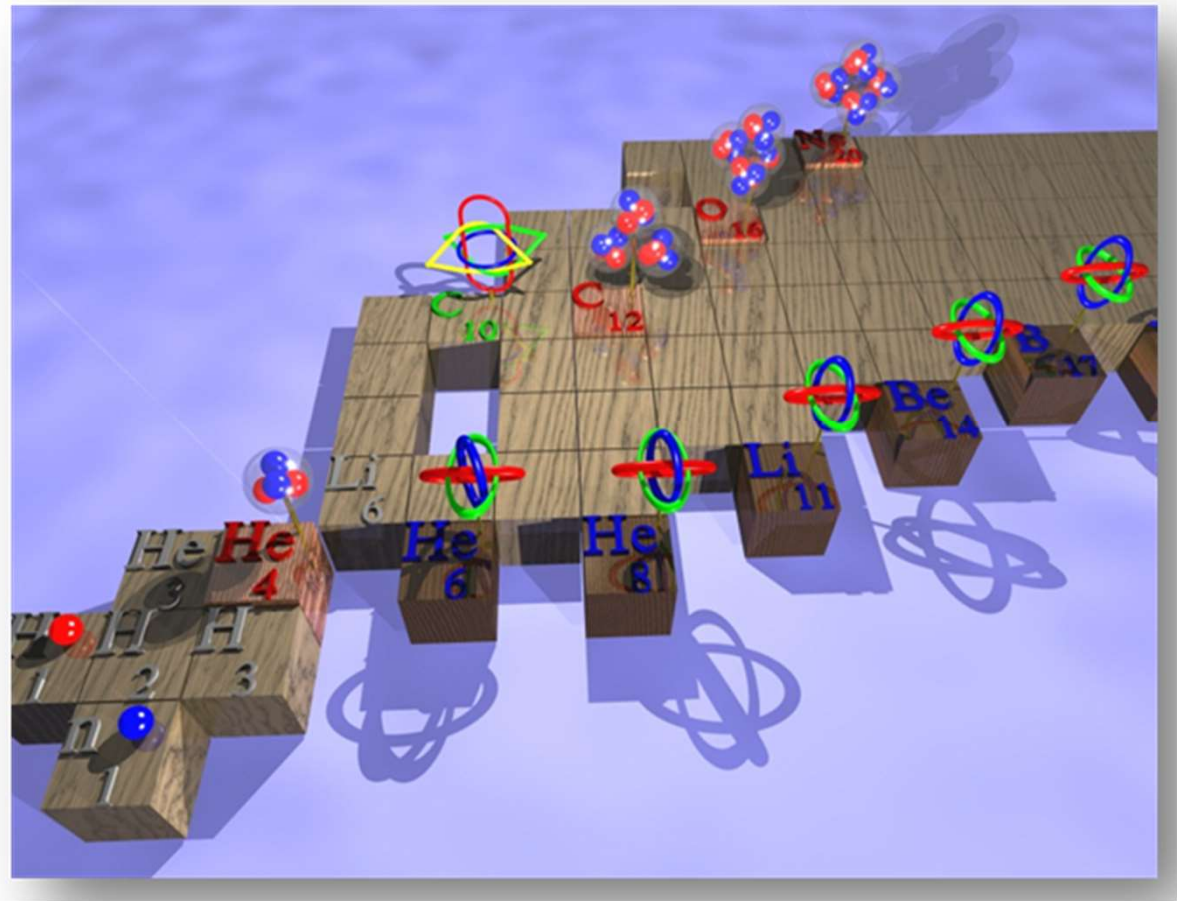
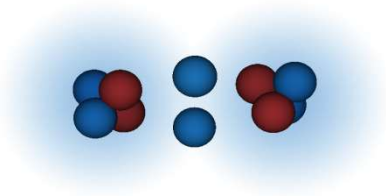
Advantages of light nuclei

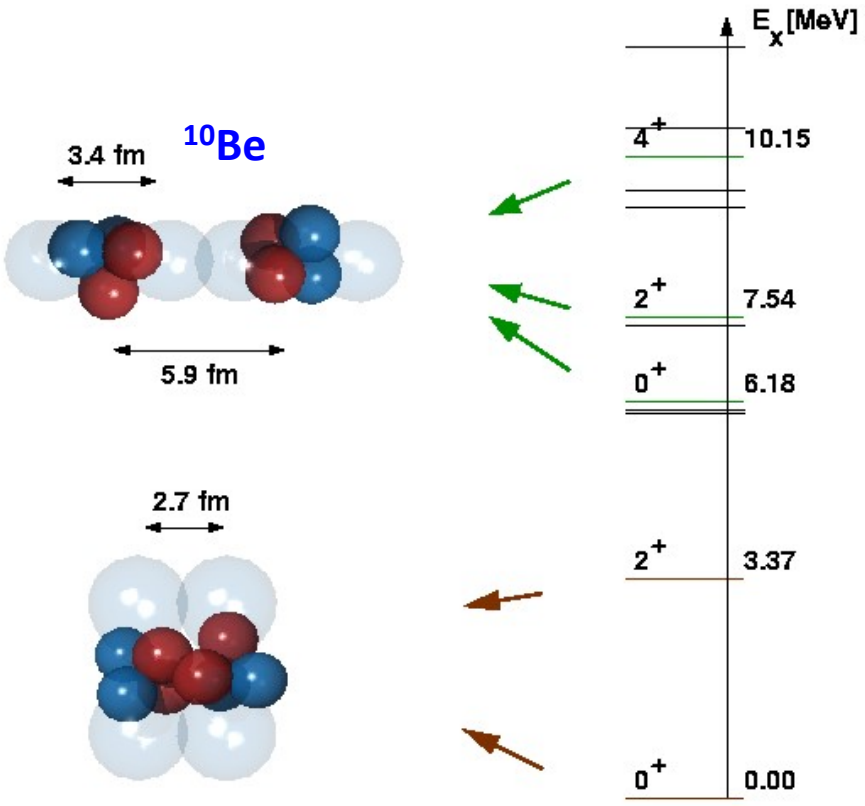
- small number of degrees of freedom
- low density of states at moderate excitations
- tests of basic principles of nuclear structure and interaction starting from individual nucleons and interaction between them
- structure & reactions: single particle – correlated pairs – clusters
- experimentally found p and n drip lines
- richness of unusall nuclear configurations: clusters, Borromean (3 and 4 component systems), skin, halo, molecules



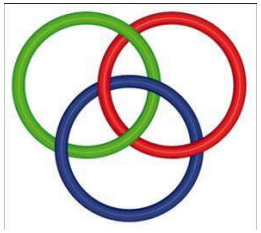
Nuclear molecules

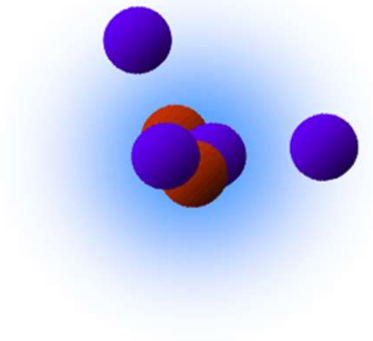
valence neutrons exchanged between the cores
9,10,^{12}Be,^{14,16}C, ^{18,20,22}O





Decay by ^{6}He emission: ^{10,12}Be signature of exotic structure - molecular structure





N.Soić *et al*, Europhys.Lett. (1995)

M.Milin *et al*, Europhys.Lett. (1999)

M.Milin *et al*, Nucl.Phys. (2005)

M.Freer *et al*, Phys.Rev.Lett. (2006)

Borromean system
neutron halo

Oxygen isotopes

^{16}O: double magic ground state, 1st excited state $^{12}C+\alpha$ cluster structure, possible 4α cluster structure at high excitations

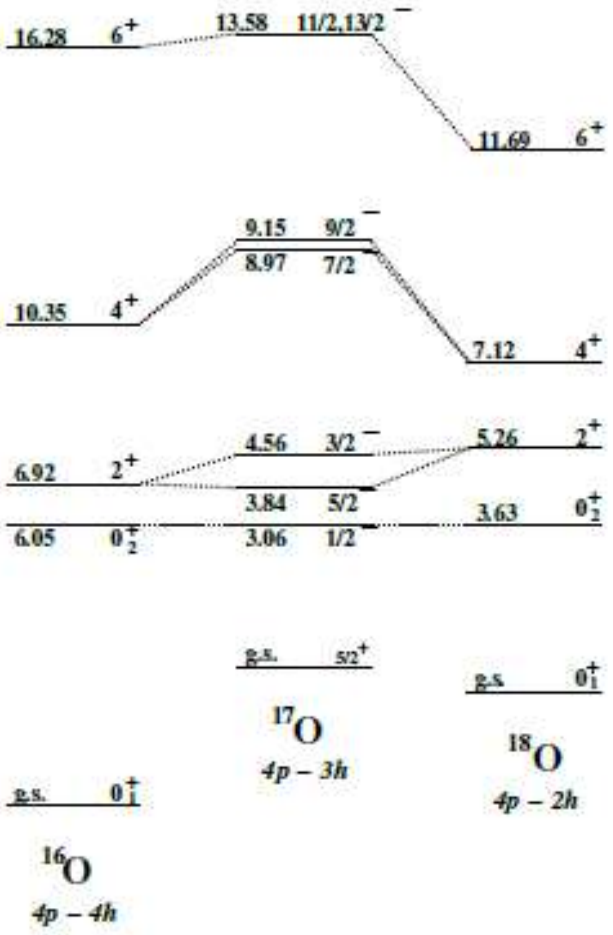
$K^{\pi}= 0^{+}$ rotational band

J^{π}	E_x MeV
0^{+}	6.05
2^{+}	6.92
4^{+}	10.36
6^{+}	16.28

$K^{\pi} = 0^{-}$ rotational band

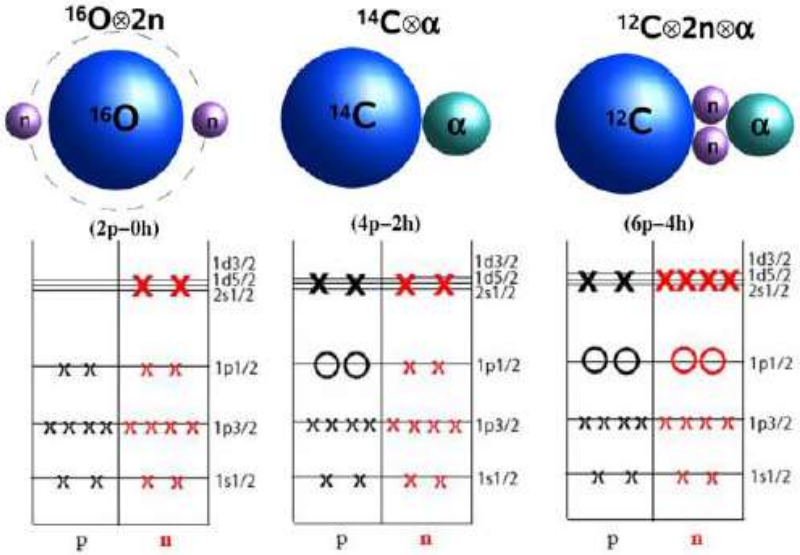
J^{π}	E_x MeV
1^{-}	9.59
3^{-}	11.60
5^{-}	14.66
7^{-}	20.86

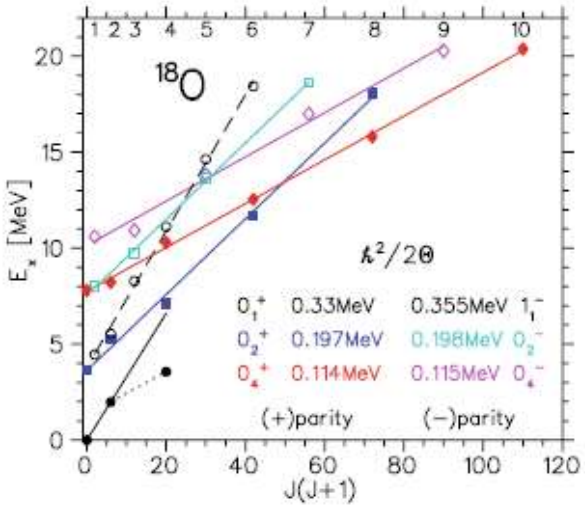
Plot of the 4p-nh states for the $^{16-18}O$

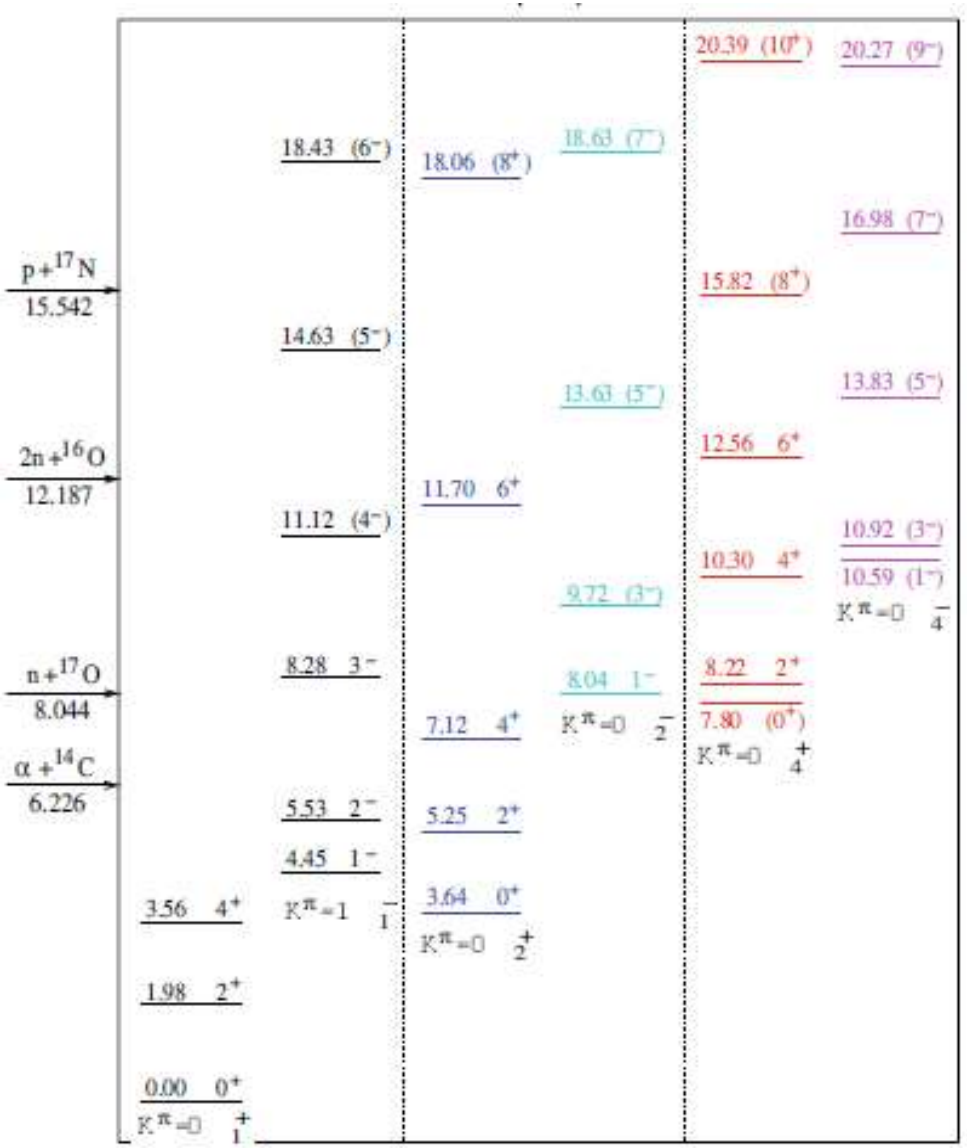


^{18}O proposed cluster configurations

W. von Oertzen et al, Eur. Phys. J. A 43 (2010) 17



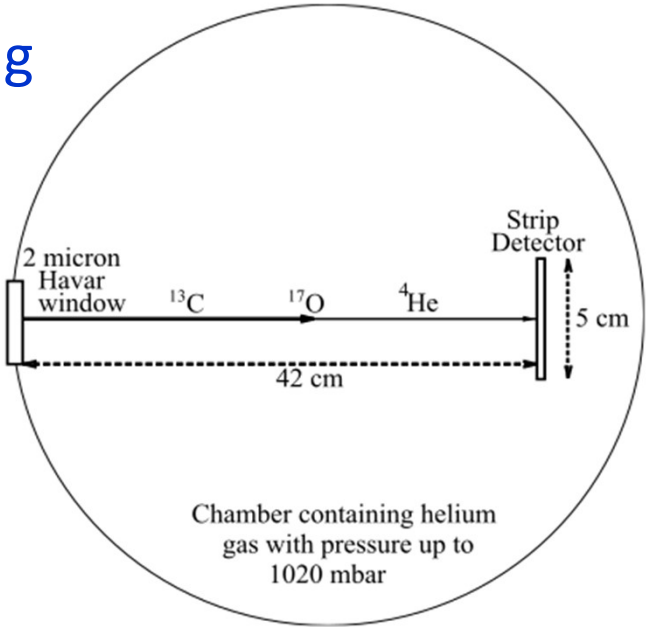


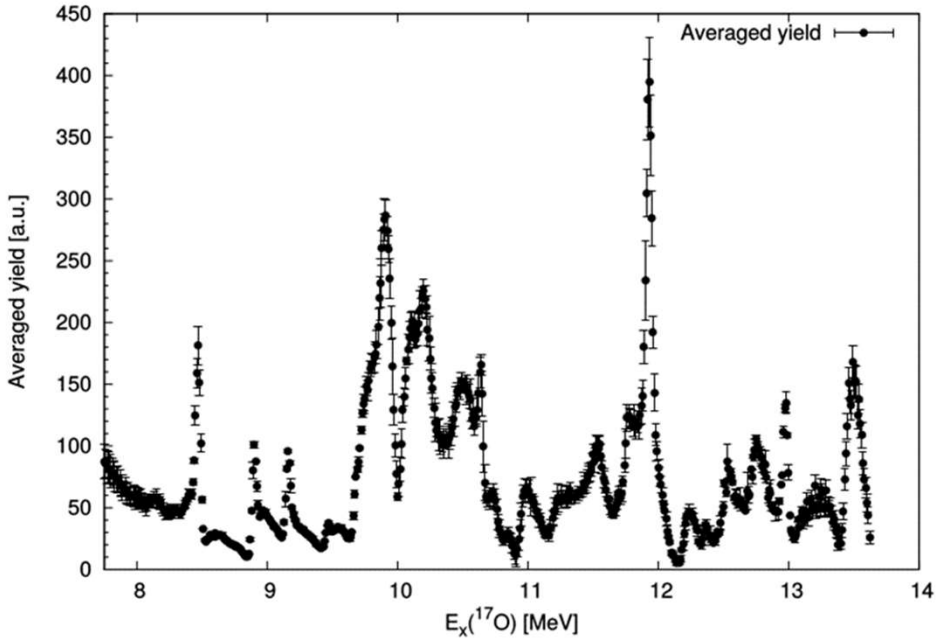


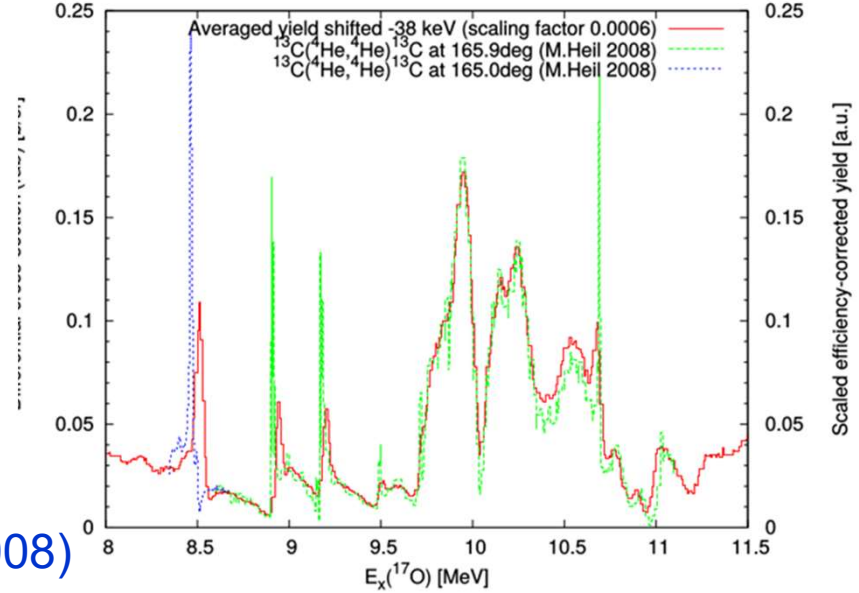
Experiment: Tandem RBI Zagreb Croatia

$^{13}C+^{4}He$ thick gas target resonant scattering

$E_{^{13}C}$ [MeV]	$p_{^{4}He}$ [mbar]	Inelastic-free $E_x(^{17}O)$ range	Run numbers
20.00	312	7.977 – 11.066	25
25.00	461	9.154 – 12.243	27
30.00	591, 589, 587	10.331 – 13.420	28-30, 32
33.00	699	11.037 – 14.126	33
35.00	720	11.508 – 14.597	35

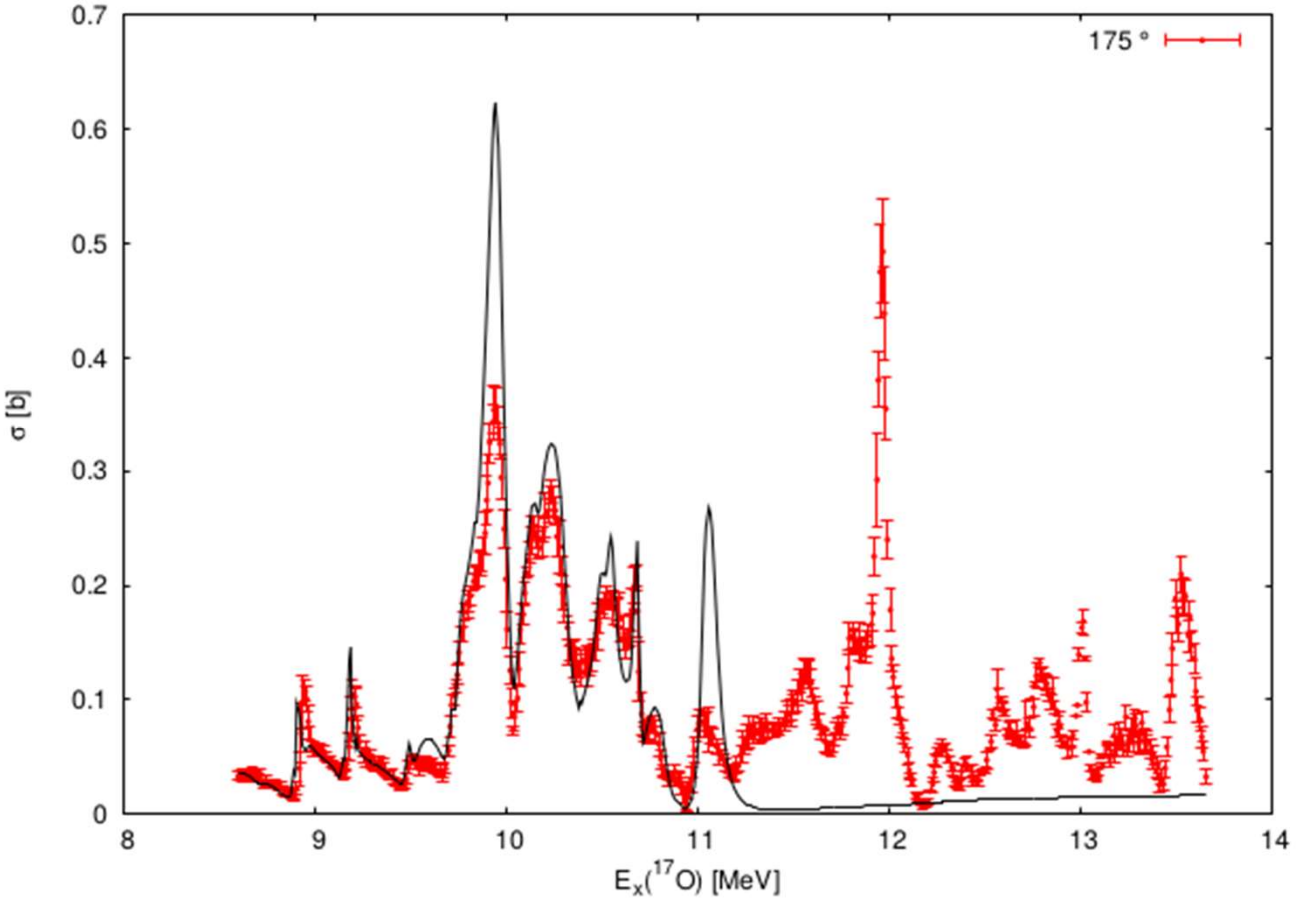






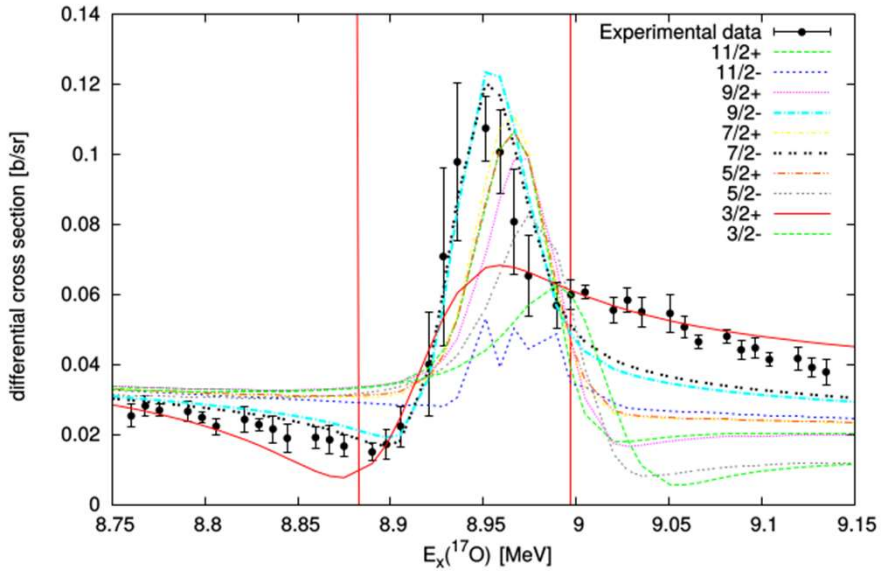
Published data: M Heil et al, PRC 78 (2008) 025803, up to excitation of 11.5 MeV

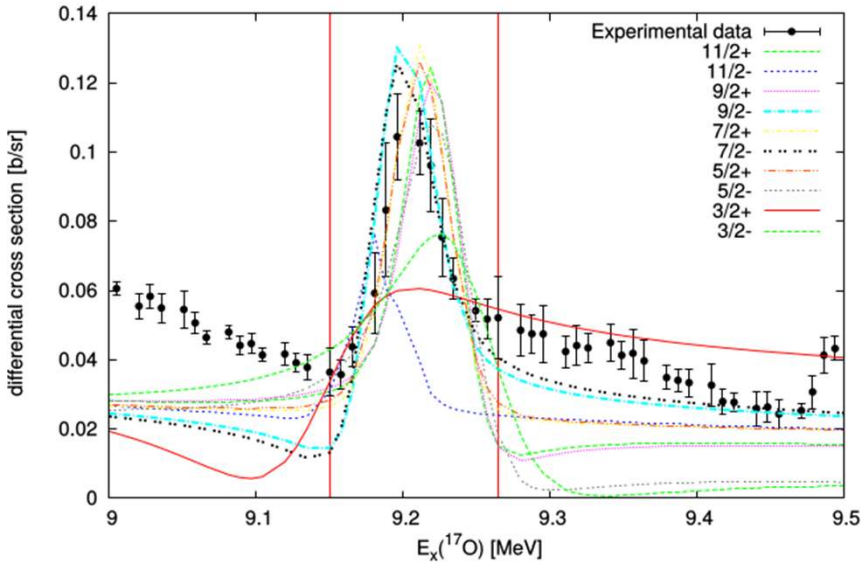
- R-matrix fits using code AZURE2 with resonance parameters from M. Heil et all (70 resonances at excitations 4.55 – 15.44 MeV obtained using code SAMMY)
- extensive fits of all available data for the $^{13}C+^{4}He$ elastic scattering at the number of angles, elastic and inelastic (1st and 2nd excited state) $^{16}O+n$ scattering, $^{13}C(^{4}He,n)$ reaction, $^{16}O(n,^{4}He)$ reaction
- significant discrepancies between fits and experimental results even for Heil data



Our results for the $^{13}C+^{4}He$ elastic scattering with R-matrix fit using published resonance parameters

Simplified R-matrix fit: single isolated resonance for single channel and single data set at one angle



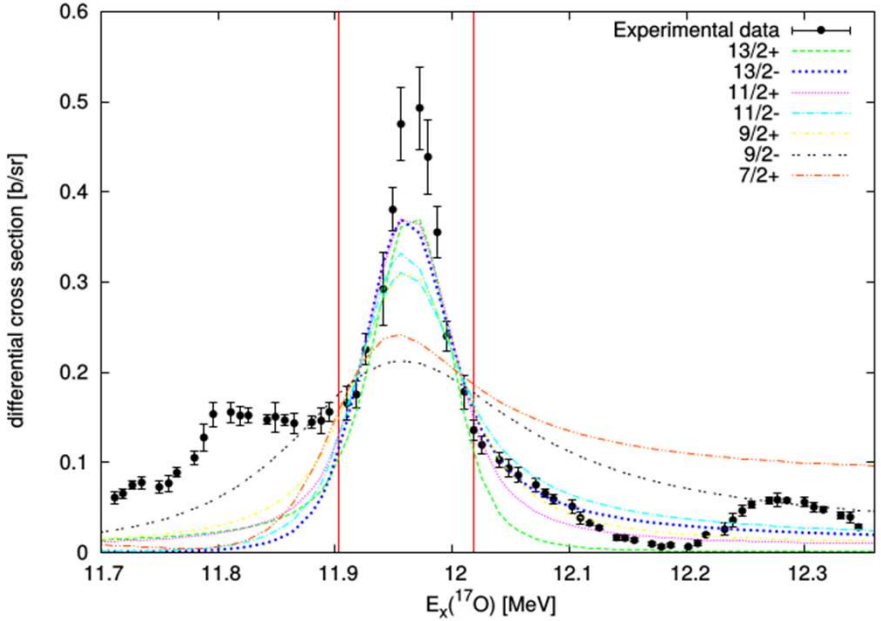


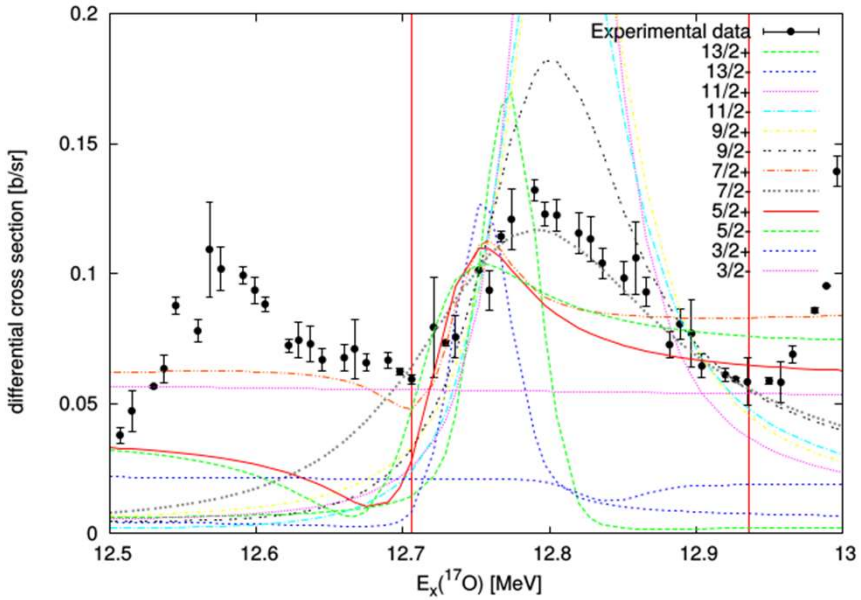
Test fits

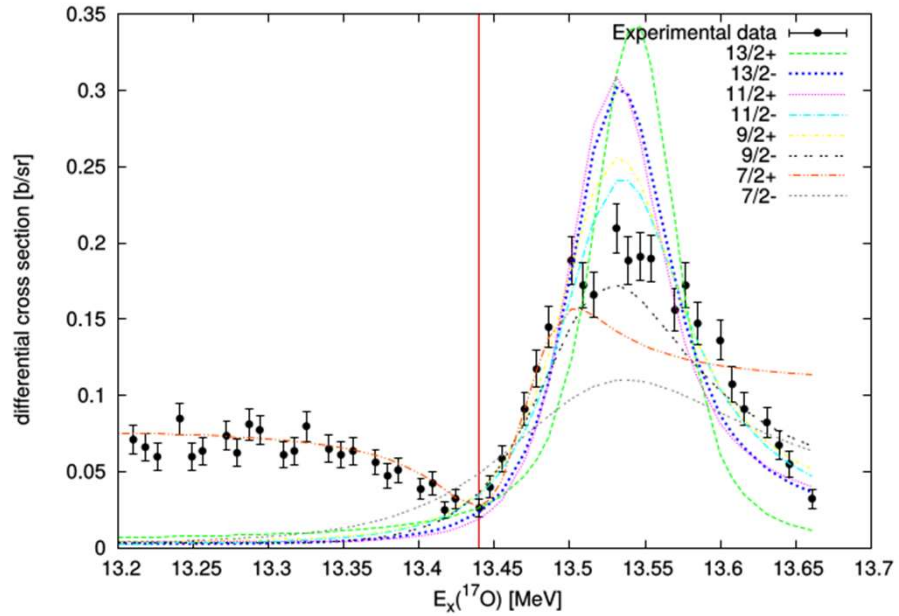
	Peak			
	8.9 MeV		9.2 MeV	
J^π	γ [MeV$^{1/2}$]	θ_W^2	γ [MeV$^{1/2}$]	θ_W^2
$\frac{9}{2}^-$	−0.482501	0.307	0.408232	0.220
$\frac{7}{2}^-$	−0.632510	0.528	0.538238	0.382

Heil et al results

J^π	$E_x(^{17}\mathrm{O})$ [MeV]	Γ_n [keV]	Γ_α [keV]
$\frac{9}{2}^-$	8.9029	$-2.3 \cdot 10^{-5}$	−0.45
$\frac{7}{2}^-$	9.1737	0.038	3.26



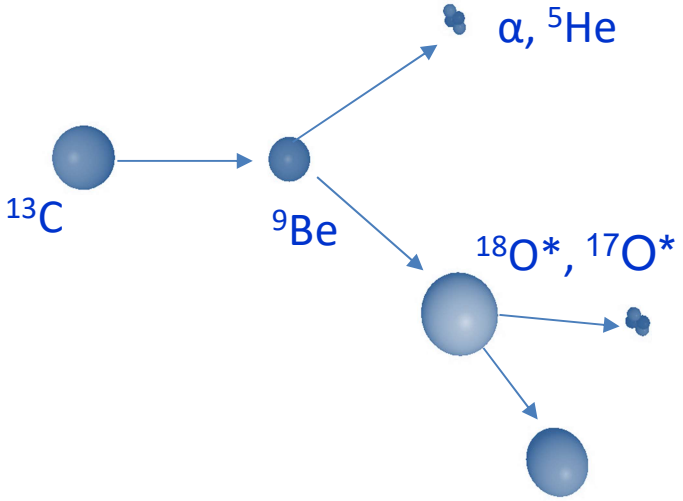




Peak								
12.0 MeV			12.8 MeV			13.6 MeV		
J^π	γ [MeV$^{1/2}$]	θ_W^2	J^π	γ [MeV$^{1/2}$]	θ_W^2	J^π	γ [MeV$^{1/2}$]	θ_W^2
$\frac{11}{2}^+$	0.339962	0.153	$\frac{7}{2}^-$	0.284347	0.107	$\frac{11}{2}^-$	0.431423	0.246
$\frac{13}{2}^-$	0.837051	0.925						

Experiment: Tandem IPN Orsay France

Kinematically complete measurements - detected 2 of 3 reaction products



$^{13}C + {}^{9}Be \rightarrow {}^{5}He + {}^{17}O^*$

$^{17}O^* \rightarrow \alpha + {}^{13}C$, Q = -2.406 MeV

$E_{thr}(\alpha + {}^{13}C) = 6.361$ MeV

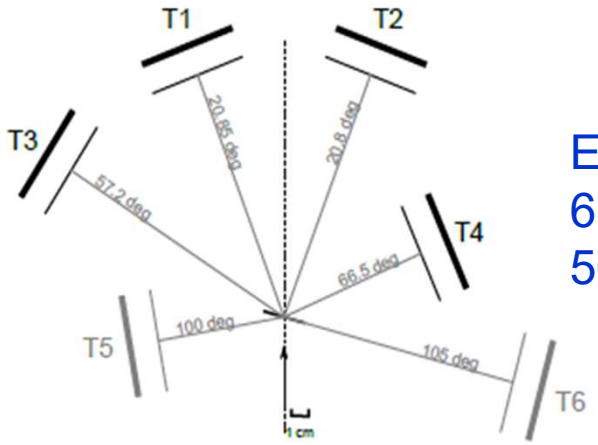
$^{13}C + {}^{9}Be \rightarrow \alpha + {}^{18}O^*$

$^{18}O^* \rightarrow \alpha + {}^{14}C$, Q = 6.604 MeV

$^{18}O^* \rightarrow {}^{6}He + {}^{12}C$, Q = -5.549 MeV

$E_{thr}(\alpha + {}^{14}C) = 6.228$ MeV

$E_{thr}({}^{6}He + {}^{12}C) = 18.380$ MeV



E(^{13}C) $_{beam}$=72 MeV, ^{9}Be target thickness 100 μg/cm^2

6 telescopes 20 μm SSSD + 1000 DSSSD μm,

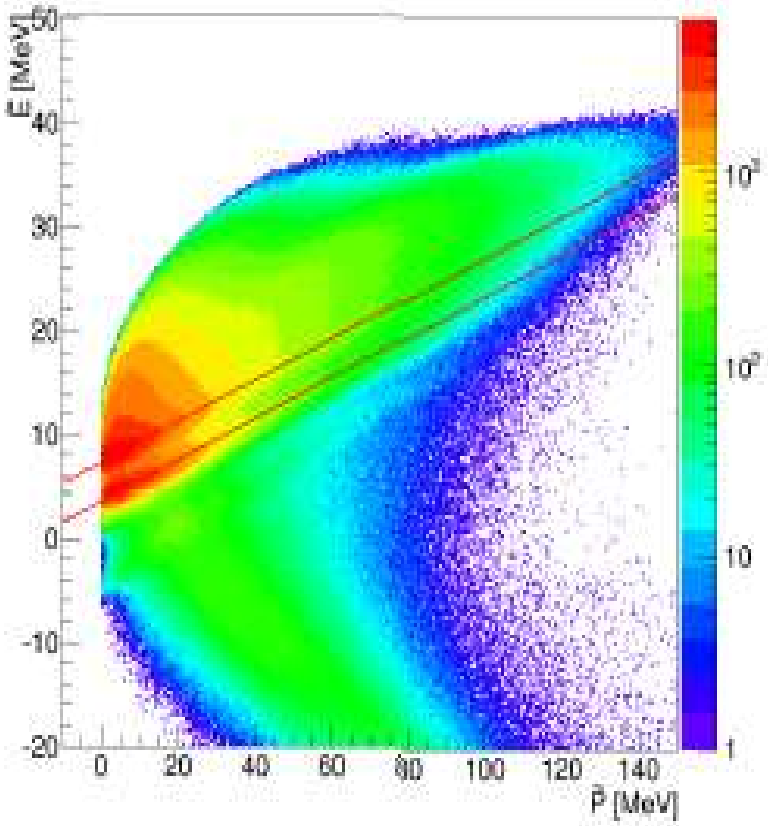
50x50 mm^2 Micron Semiconductor type W1

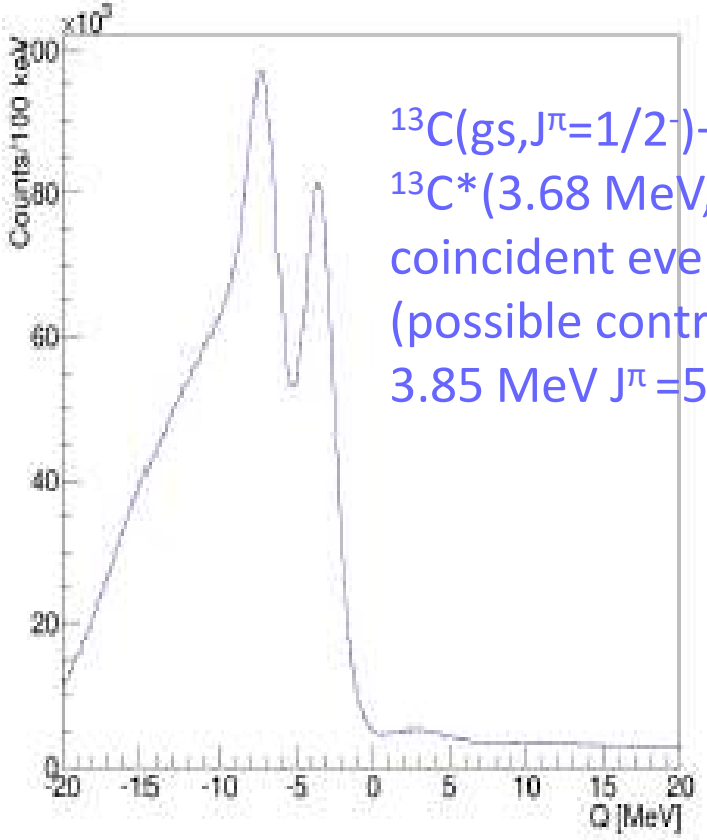
Goal: characterization of the $^{17,18}O$ resonances decaying by helium emission in excitation energy range 7 - 25 MeV: excitation energy, widths

^{17}O results

^{9}Be + ^{13}C → ^{13}C + ^{4}He+ ^{5}He (Γ=0.648 MeV)

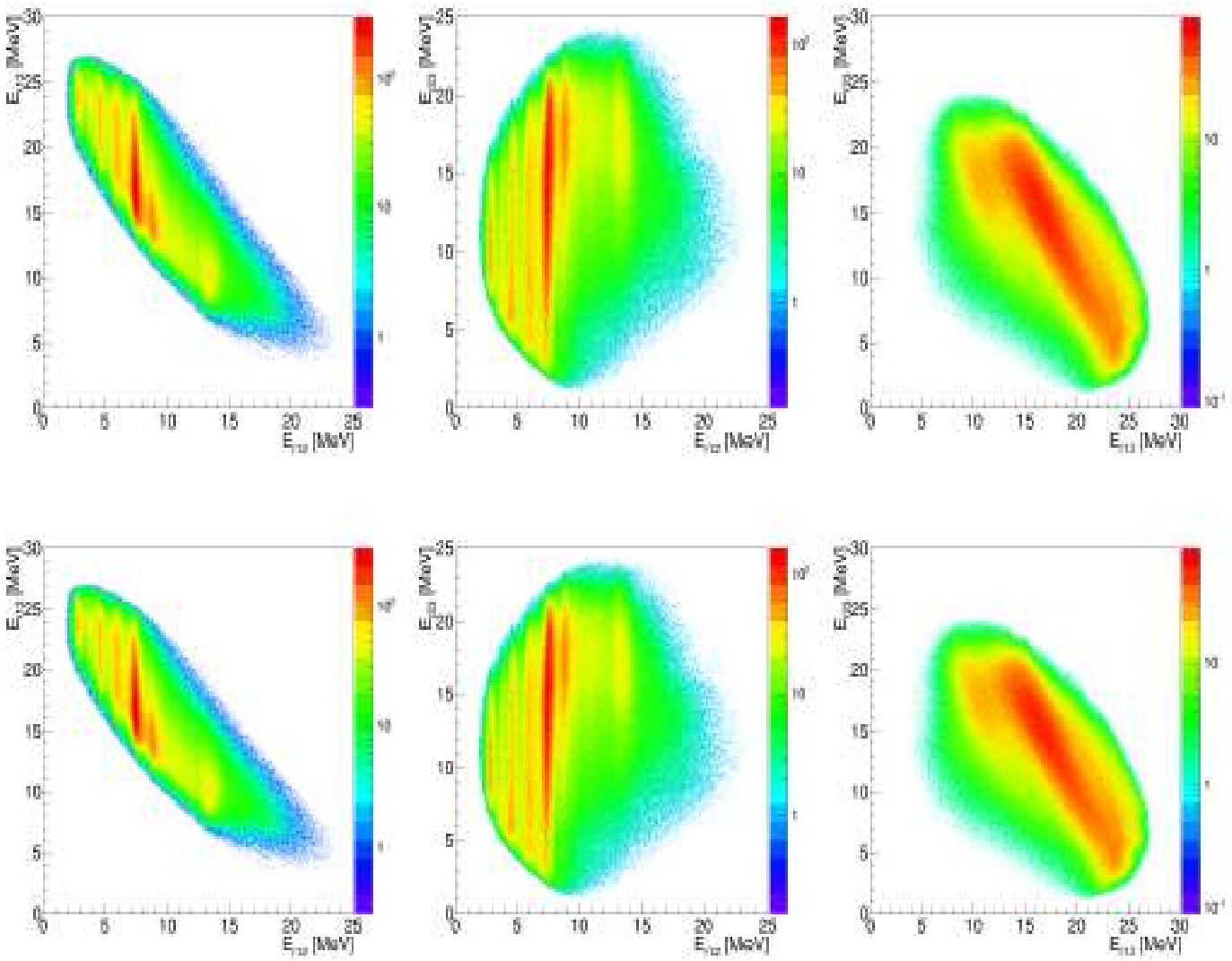
^{13}C(T1)-^{4}He(T2), ^{13}C(T2)-^{4}He(T1), ^{13}C(T1)-^{4}He(T4) & ^{13}C(T2)-^{4}He(T3) coincident events





^{13}C(gs,J$^{\pi}$=1/2^{-})+^{4}He and ^{13}C*(3.68 MeV, J$^{\pi}$=3/2^{-})+^{4}He coincident events in T1-T2. (possible contribution of the 3.85 MeV J$^{\pi}$ =5/2^{+})

Reaction identification: Catania plot & Q-value plot



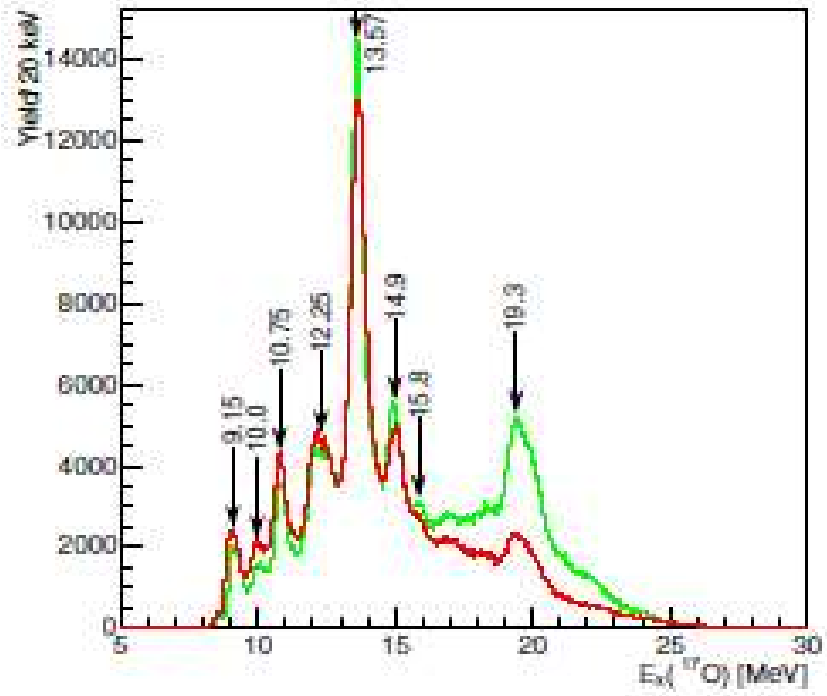
Exit channel
$^{13}C+^{4}He+^{5}He$

$^{17}O=^{13}C+^{4}He$
T1-T2 events

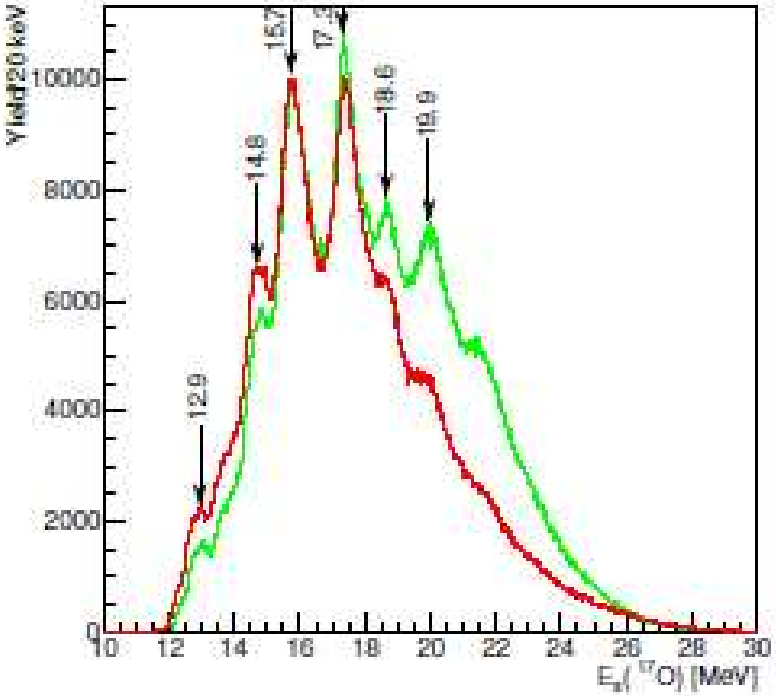
$^{9}Be=^{4}He+^{5}He$
T1-T4, T2-T3 events

$^{18}O=^{13}C+^{5}He$
not observed

Relative-energy plots for the $^{9}Be(^{13}C,^{13}C^{4}He)^{5}He$ reaction. The ^{13}C(T1/T2), ^{4}He(T2/T1) and ^{5}He (undetected) are labeled by numbers 1, 2 and 3.



The ^{17}O excitation energy spectrum from the ^{13}C(gs, $J^{\pi}=1/2^{-}$)+^{4}He coincident events in T1-T2 (red) and T2-T1 (green).



The ^{17}O excitation energy spectrum from the $^{13}C^{*}$(3.68 MeV, $J^{\pi}=3/2^{-}$)+^{4}He coincident events in T1-T2 (red) and T2-T1 (green) (possible contribution 3.85 MeV $J^{\pi}=5/2^{+}$)

No.	$^{13}C+^{4}He$ res. el.		$^{13}C+^{9}Be$ reactions		References	Tilley *et. al.* [50]	
	E_x [MeV]	J^π	$^{13}C+^{4}He$ coinc.	$^{13}C^*+^{4}He$ coinc.		E_x [MeV]	J^π
1	8.9	$\left(\frac{7}{2}^-\right)$ or $\left(\frac{9}{2}^-\right)$			[7]		
2	9.2	$\left(\frac{7}{2}^-\right)$ or $\left(\frac{9}{2}^-\right)$	9.15		[5], [7], [98], [101], [102]	9.147	$\frac{1}{2}^-$
3	10.0†		10.0		[7]	9.976	$\frac{5}{2}^-$
4	10.75†		10.75		[6], [100], [101]	10.777	$\frac{1}{2}^+, \frac{7}{2}^-$
5	12.0	$\left(\frac{11}{2}^+\right)$ or $\left(\frac{13}{2}^-\right)$	12.25 (wide)		[61], [96], [97], [98]	12.005 ± 15	$> \frac{3}{2}$
6	12.8			12.9	[100]	12.93	
7	13.6	$\left(\frac{11}{2}^-\right)$	**13.57**		[4], [5], [98], [100]	13.58	$(\frac{11}{2}, \frac{13}{2})^-$
8			14.9	14.8	[4], [6], [100]	15.1 ± 0.1	$\left(\frac{9}{2}^+, \frac{11}{2}^+\right)$
9			15.8	**15.7**	[4], [6]*, [100], [103],	15.95	$\left(\frac{9}{2}^+, \frac{11}{2}^+\right)$
10			(weak peak)	**17.3**	[3], [6]*, [98], [105]	17.06	$\frac{11}{2}^-$
11			(weak peak)	18.6	[6]*	18.72	
12			19.3		[6], [4], [104]		
13				19.6	[3], [6]*	19.6	$\left(\frac{13}{2}^+, \frac{15}{2}^+\right)$

Published results:

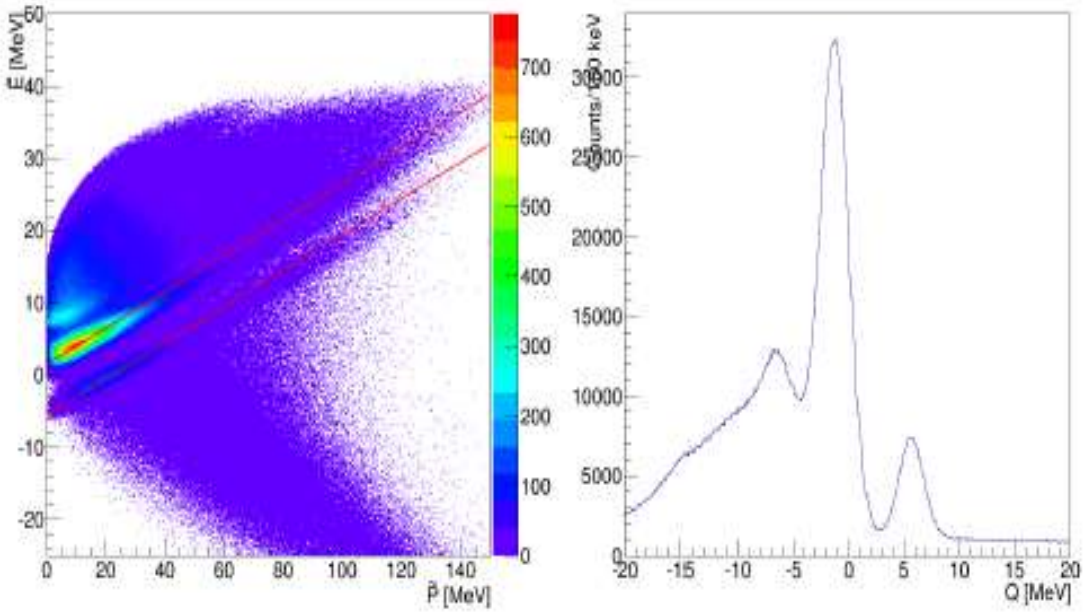
(6) M. Milin et al, EPJ A 41 (2009) 335, the same reaction

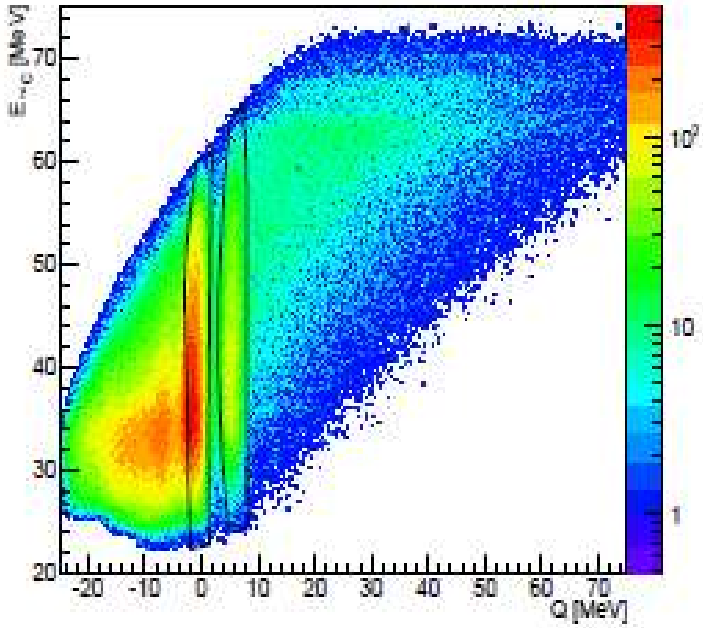
(7) M. Heil et al, PRC 78 (2008) 025803, the $^{13}C+^{4}He$ thick target resonant scattering up to excitation 11.1 MeV

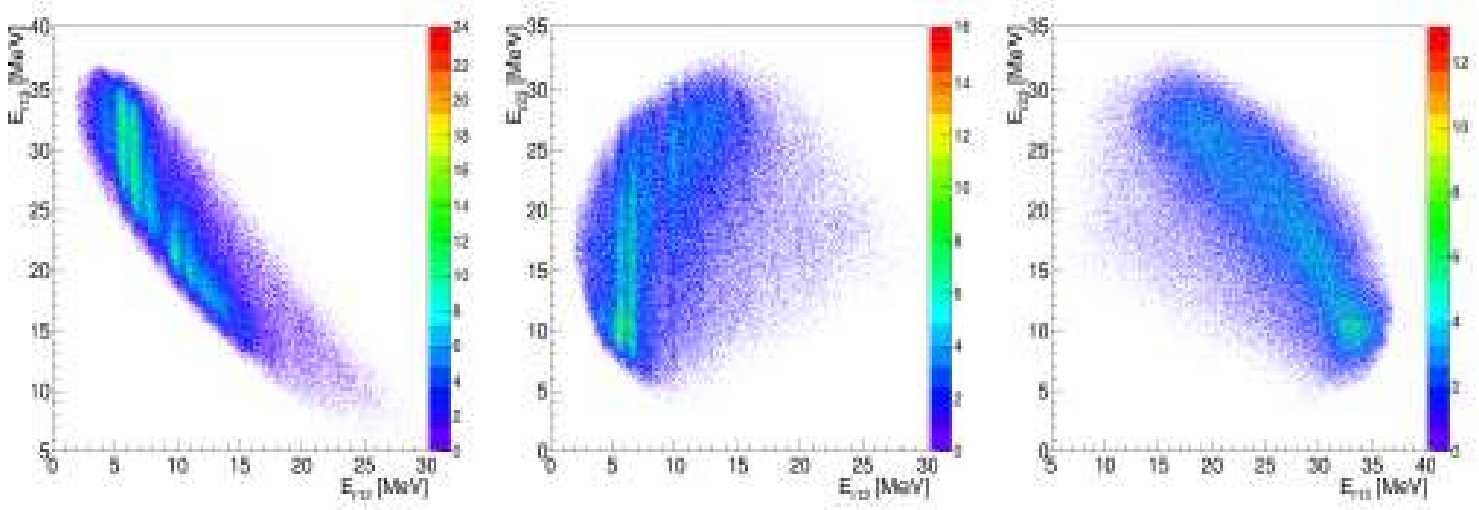
^{18}O results

$^{9}Be+^{13}C \rightarrow ^{4}He+^{18}O^{*} \rightarrow$
$^{14}C+^{4}He+^{4}He$, $^{14}C^{*}$(E ≈7 MeV $0^{-},2^{+}2^{-}$)$+^{4}He+^{4}He$
$^{12}C+^{6}He+^{4}He$, $^{12}C^{*}$(E^{*}=4.4MeV 2^{+})$+^{6}He+^{4}He$
$^{10}Be+^{8}Be+^{4}He$, $^{10}Be^{*}$ (E =3.37MeV 2^{+}; ≈6.2 MeV $2^{+},1^{-},0^{+},2^{-}$) $+^{8}Be+^{4}He$
Events for all possible telescope combinations

^{14}C(T1)-^{4}He(T2) 14C(gs, $J^{\pi}=0^{+}$)$+^{4}$He & $^{14}C^{*}$(7 MeV)$+^{4}$He in T1-T2

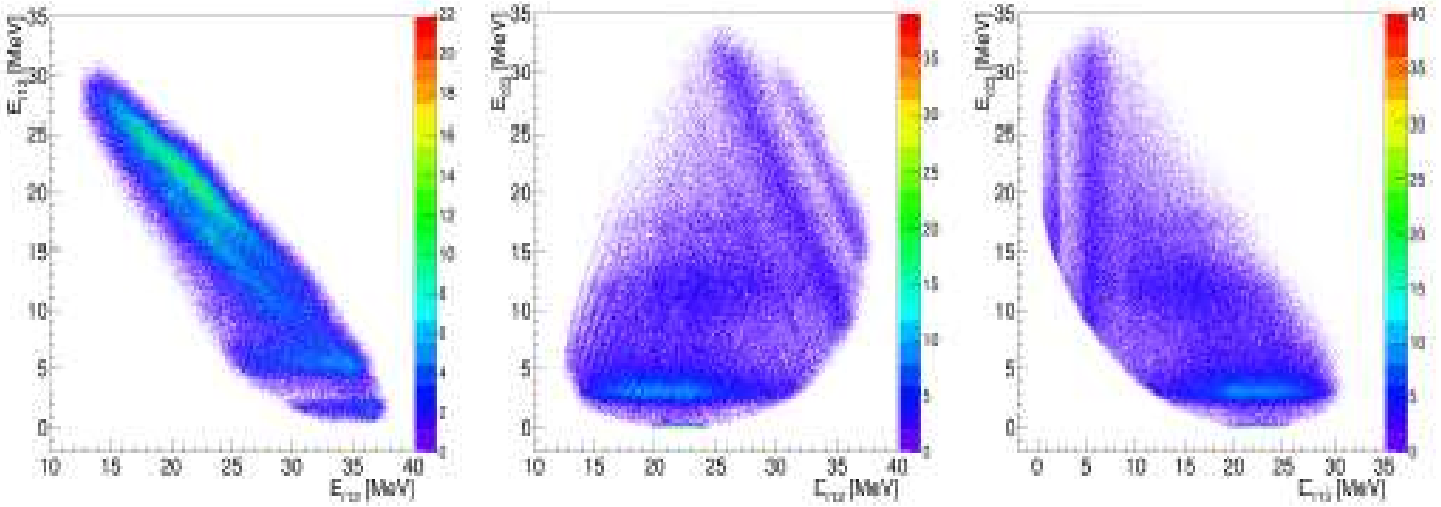




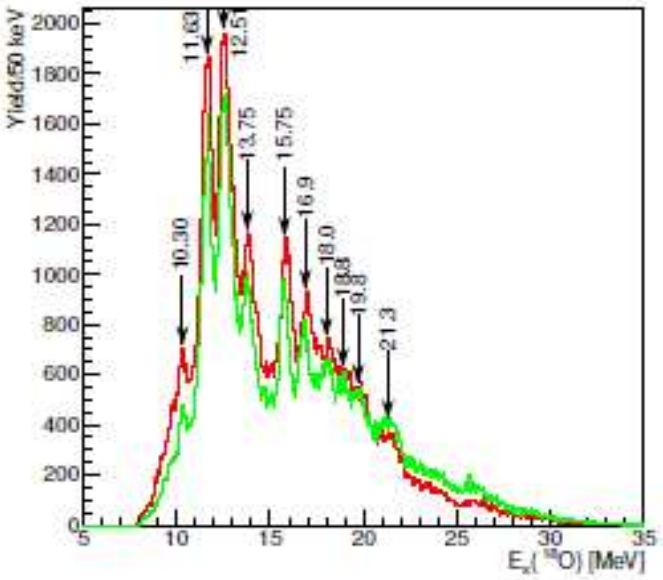


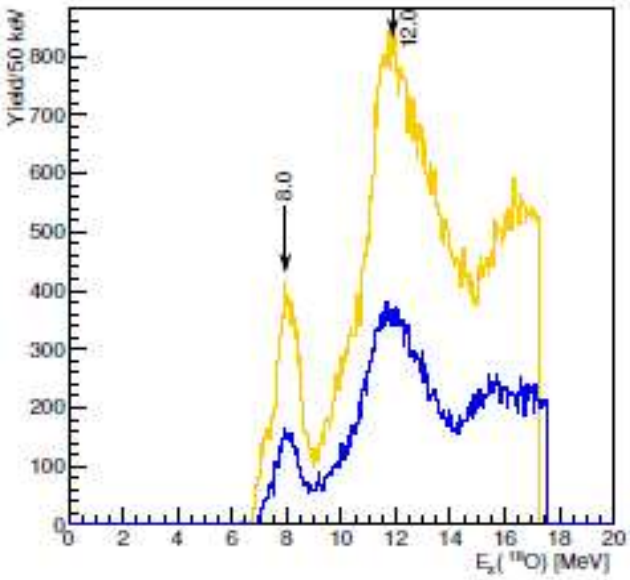
Relative-energy plots for the ^{9}Be(^{13}C,^{14}C^{4}He)^{4}He reaction. The ^{14}C(T1), ^{4}He(T2) and ^{4}He (undetected) are labeled by numbers 1, 2 and 3.

graphical cuts

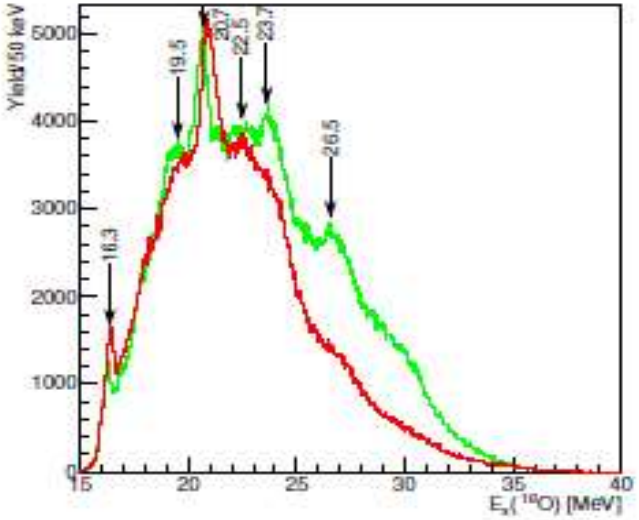


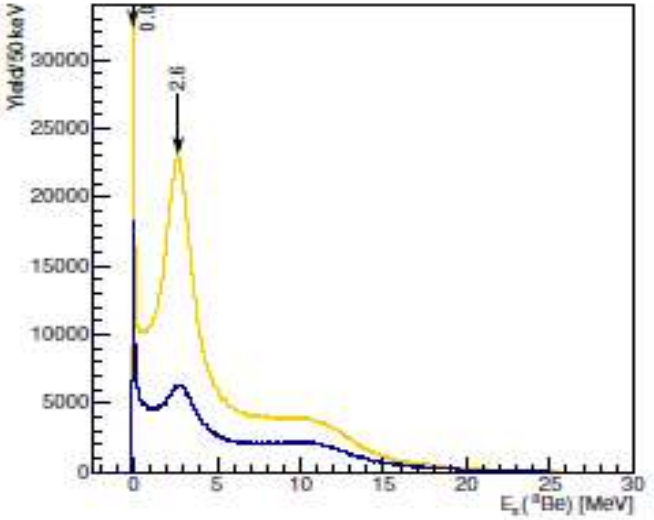
Relative-energy plots for the ^{9}Be(^{13}C,^{14}C^{4}He)^{4}He reaction. The ^{14}C(T1), ^{4}He(T4) and ^{4}He (undetected) are labeled by numbers 1, 2 and 3.





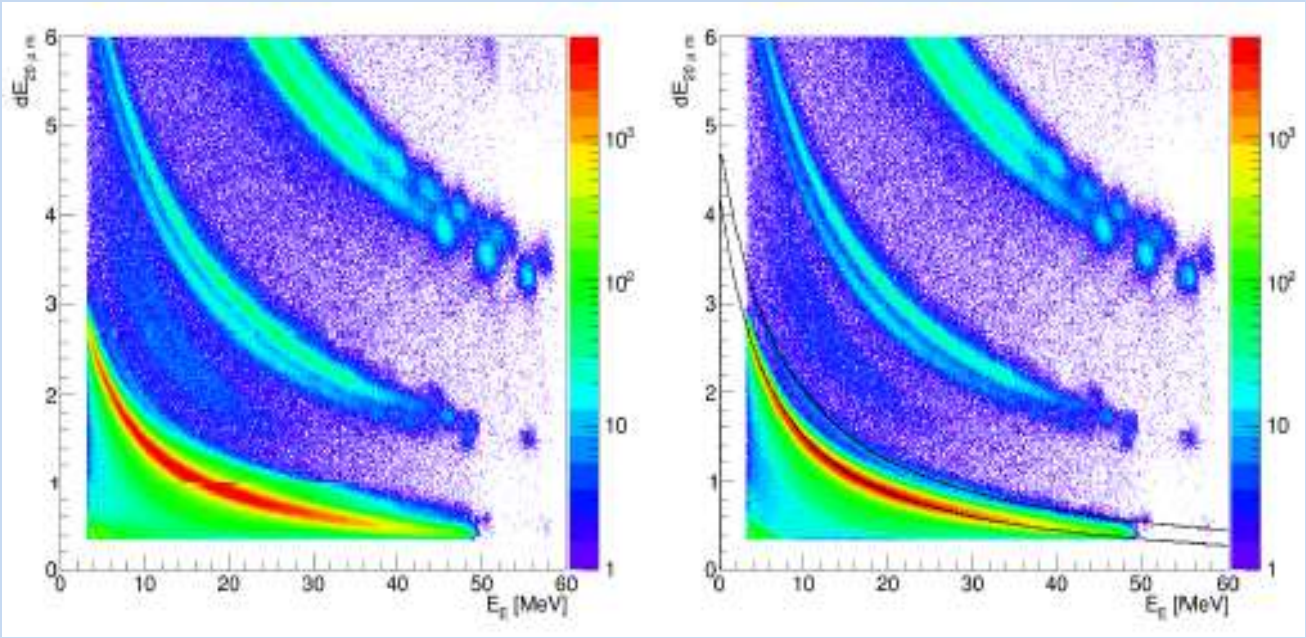
The ^{18}O excitation energy spectrum for the $^{14}C(gs)+^{4}He$ coincident events in T1-T2 (red), T2-T1 (green), T1-T4 (orange) and T2-T3 (blue).



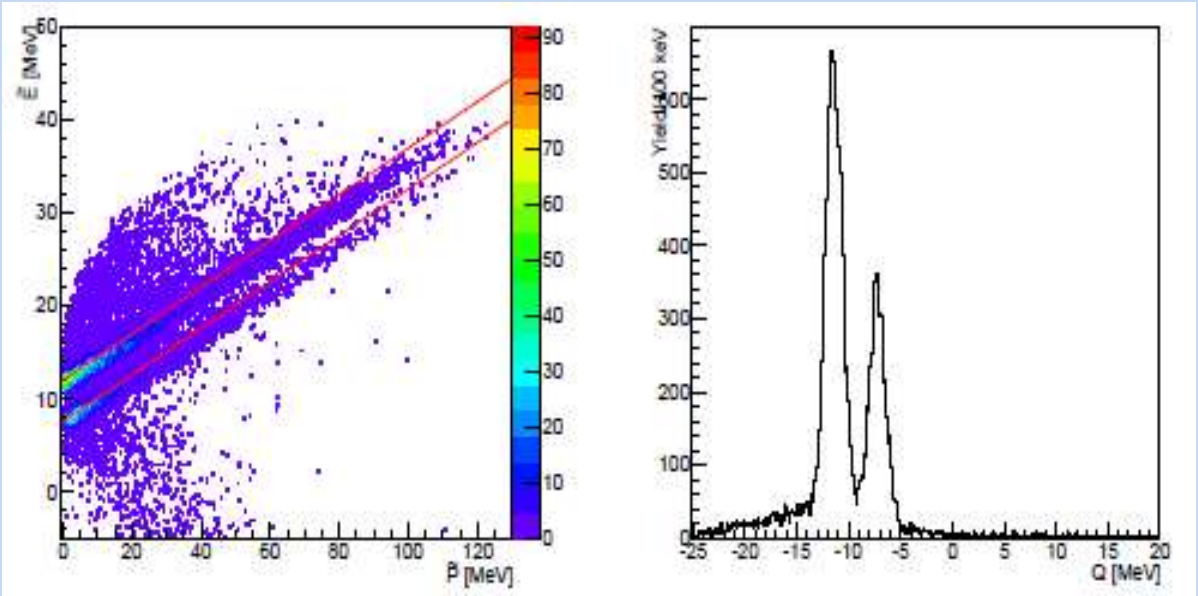


The ^{18}O excitation energy spectrum for the $^{14}C^{*}(7\ MeV)+^{4}He$ events in T1-T2 (red) and T2-T1 (green);
^{8}Be spectrum for T1-T4 (orange) and T2-T3 (blue).

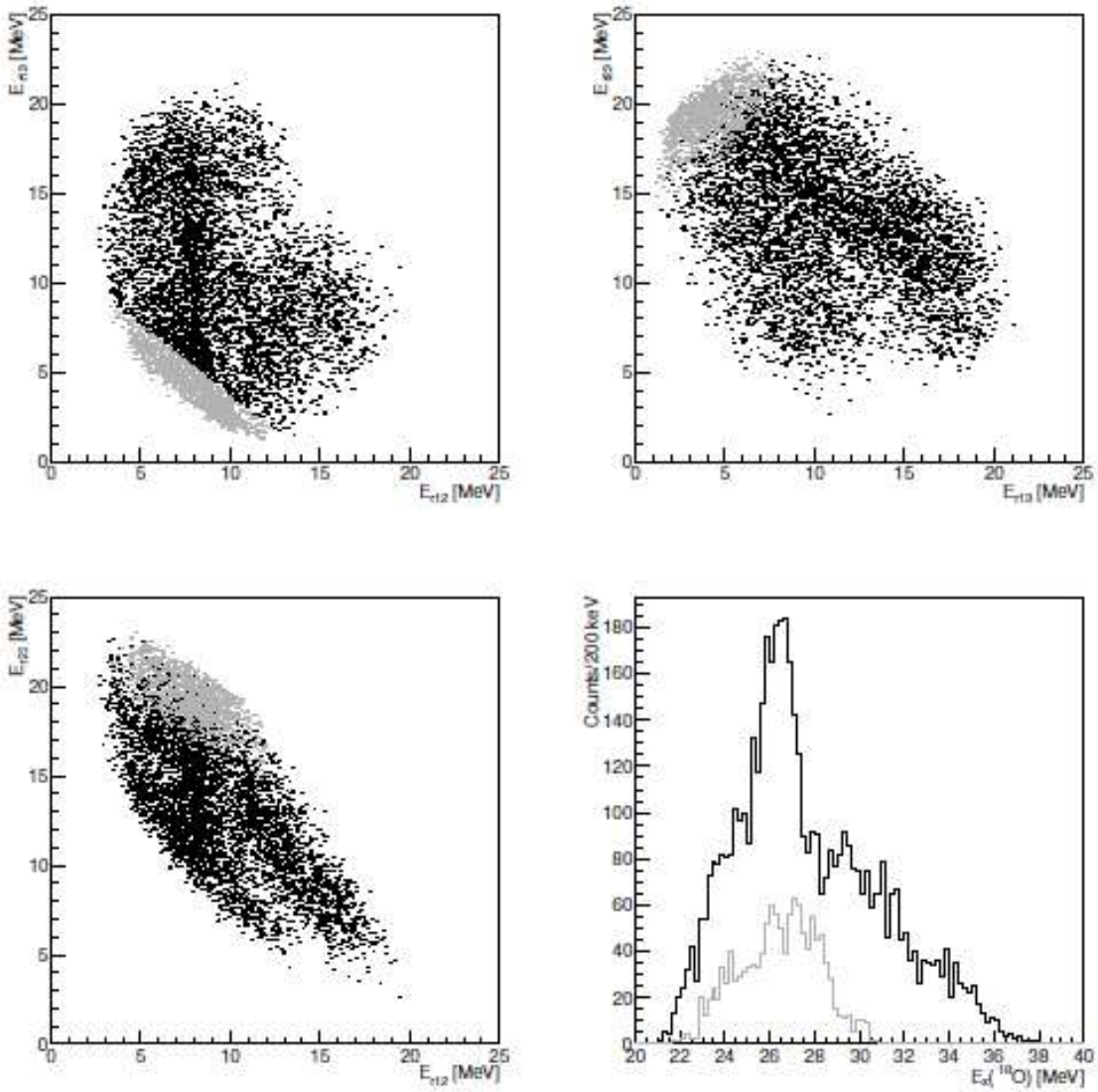
$^{9}Be + ^{13}C \rightarrow ^{12}C + ^{6}He + ^{4}He$



Additional ΔE-E spectra filtering to separate ^{6}He from ^{4}He for the T1, ΔE-strip 8. Black lines show results of simulations for $^{4,6}He$ in T1



The Catania plot for the ^{6}He detected in T1 and ^{12}C in T2. The red lines are predicted loci for the $^{9}Be(^{13}C,^{6}He^{12}C(gs))^{4}He$ $^{9}Be(^{13}C,^{6}He^{12}C^{*}(4.4\ MeV))^{4}He$.



broad peak at 26.5 MeV, indications of peaks at 29.5 MeV and around 23.5 MeV.

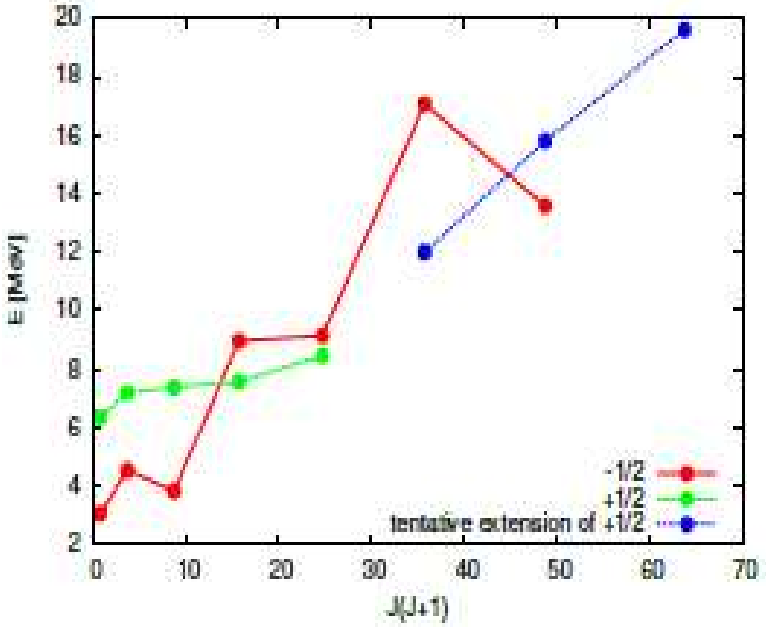
E -E plots for ^{6}He and ^{12}C(gs) detected in T1 and T2, labelled as 1 and 2. The last plot is the ^{18}O excitation energy spectrum for events selected via graphical cut (black dots). The grey dots correspond to events from the ^{16}O decay. For the ^{12}C*(4.4 MeV)+^{6}He events excitation spectrum is structureless.

No.	$E_x(^{18}O)$ from the $^{13}C+^{9}Be$ reactions			References	Tilley *et. al.* [87]	
1	$^{14}C+^{4}He$	$^{14}C^{*}+^{4}He$	$^{12}C+^{6}He$		E_x [MeV]	J^{π}
2	10.30 MeV			[12], [13], [14], [106], [107], [108], [109], [110], [111], [112], [113], [114]	10.290 MeV	4^{+}
3	**11.63 MeV**			[12], [13], [14], [101], [106], [107], [108], [109], [111], [113]	11.62 MeV	5^{-}
4	**12.51 MeV**			[12], [13], [14], [106], [107], [108], [109], [111]	12.53 MeV	6^{+}
5	**13.75 MeV**			[111]	13.8	1^{-}
6				[13], [14]	13.82	5^{-}
7	15.75 MeV			[111]	15.8	1^{-}
8		**16.1 MeV**		[12]	16.315	$(3,2)^{-}$
9	16.9 MeV			[107], [109]	16.948	$(2,3)^{-}$
10	18.0 MeV			[115]	18.049	
11	18.8 MeV			[110], [115]	18.68	(4^{-})
12		19.3 MeV				
13	19.8 MeV					
14		**20.5 MeV**		[110]	20.86	
15	21.3 MeV			[110], [117]	21.42	(4^{-})
16		22.3 MeV		[110]	22.4	4^{-}
17		23.5 MeV	23.5 MeV	[110], [116]	23.8	1^{-}
18		26.3 MeV	26.5 MeV	[116]	27	1^{-}
19			29.5 MeV	[116]	30	

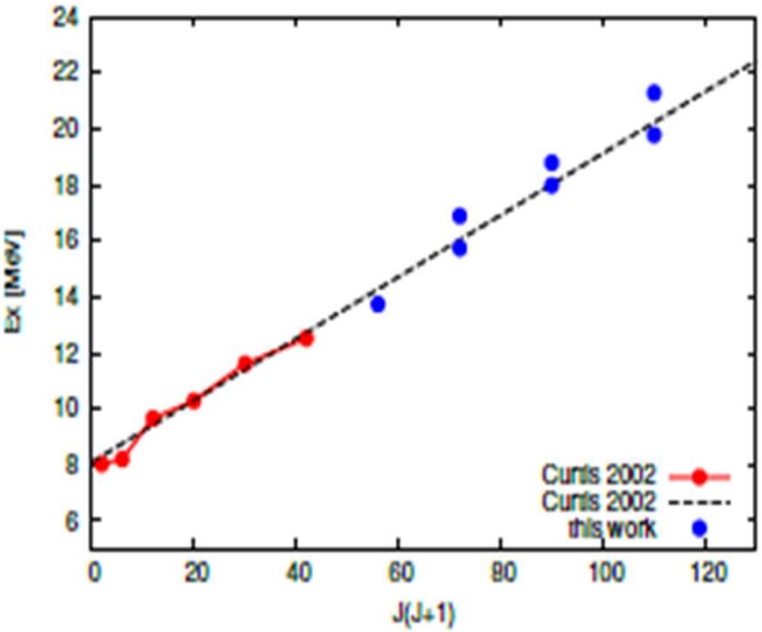
Published many results, some recent:

(14) M. L. Avila et al, PRC 90 (2014) 024327, the $^{14}C+^{4}He$ thick target resonant scattering

(12) N. Curtis et al, PRC 66 (2002) 024315, $^{14}C(^{18}O,^{14}C^{4}He)^{14}C$



A tentative extension of the proposed ^{17}O positive-parity rotational band and the negative-parity rotational band.



A tentative extension of the proposed ^{18}O rotational band. In agreement with proposed rotational bands in W. von Oertzen et al, EPJ A 43 (2009) 17

Summary & outlook

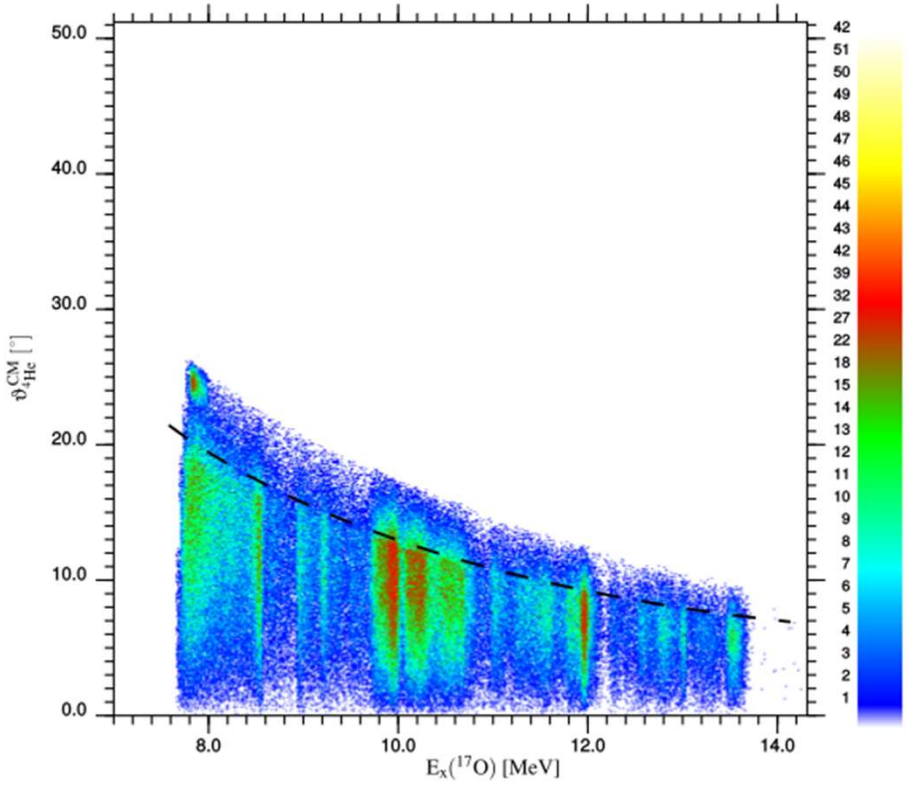
- the resonant scattering $^{13}C+^{4}He$ experiment and resonant nucleus spectroscopy experiment with the $^{13}C+^{9}Be$ reaction populated excited states with cluster structure in the ^{17}O and ^{18}O (RPSE)
- existing results on the ^{4}He decays confirmed and extended
- the ^{6}He decaying states in ^{18}O have been observed for the first time – the first indication of the molecular structure ^{12}C-2n-^{4}He
- no ^{5}He & ^{8}Be decays observed
- these measurements should be complemented with other technique experiments, for example thick target resonant scattering measurements
- further measurements using different techniques are needed to determine the exact value of spin and parity, with higher resolution and statistics to separate nearby states – some of them will be run soon
- there are indications that molecular structure exist in oxygen isotopes but much more experimental data are required

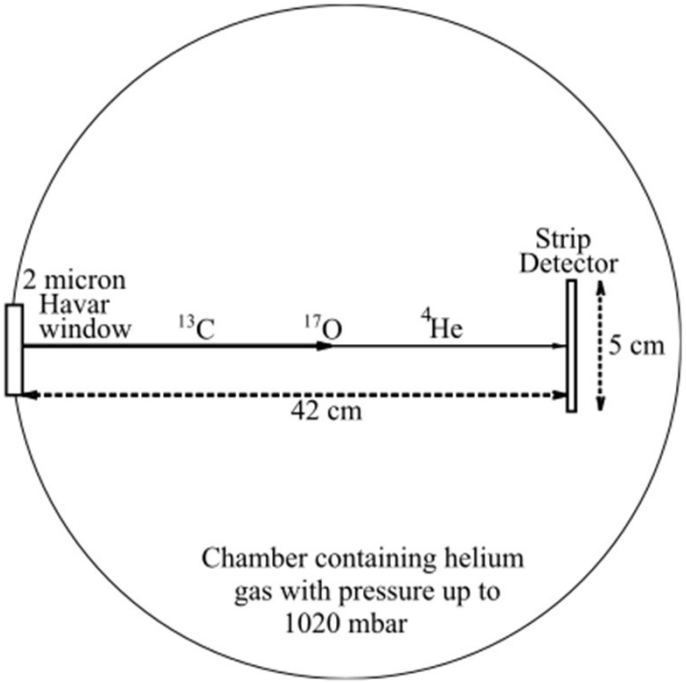
Thank you !

Experiment: Tandem RBI Zagreb Croatia

$^{13}C+^{4}He$ thick gas target resonant scattering

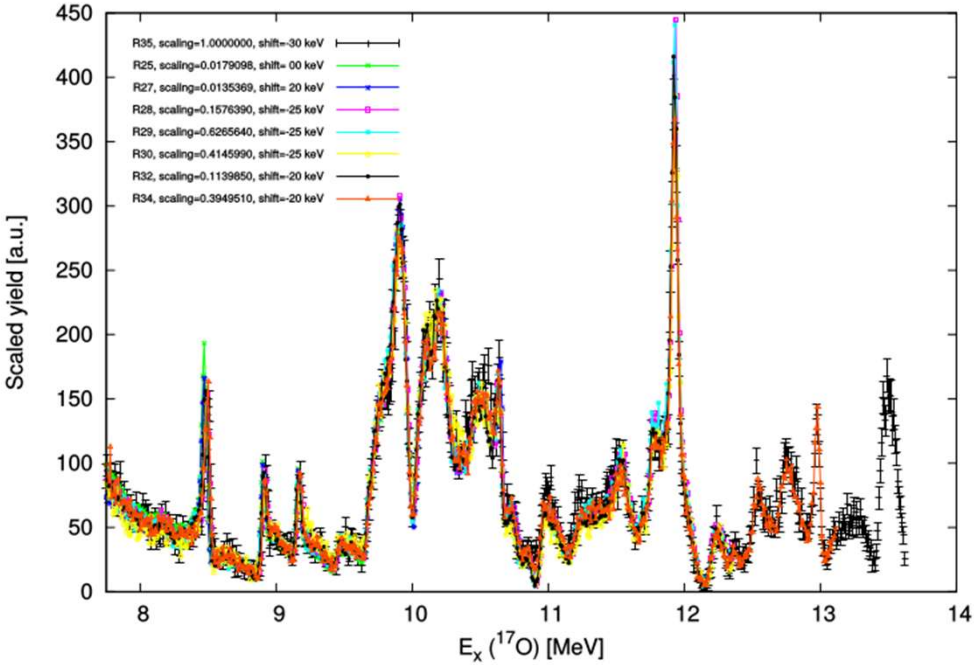
$E_{^{13}C}$ [MeV]	$p_{^{4}He}$ [mbar]	Inelastic-free $E_x(^{17}O)$ range	Run numbers
20.00	312	7.977 – 11.066	25
25.00	461	9.154 – 12.243	27
30.00	591, 589, 587	10.331 – 13.420	28-30, 32
33.00	699	11.037 – 14.126	33
35.00	720	11.508 – 14.597	35





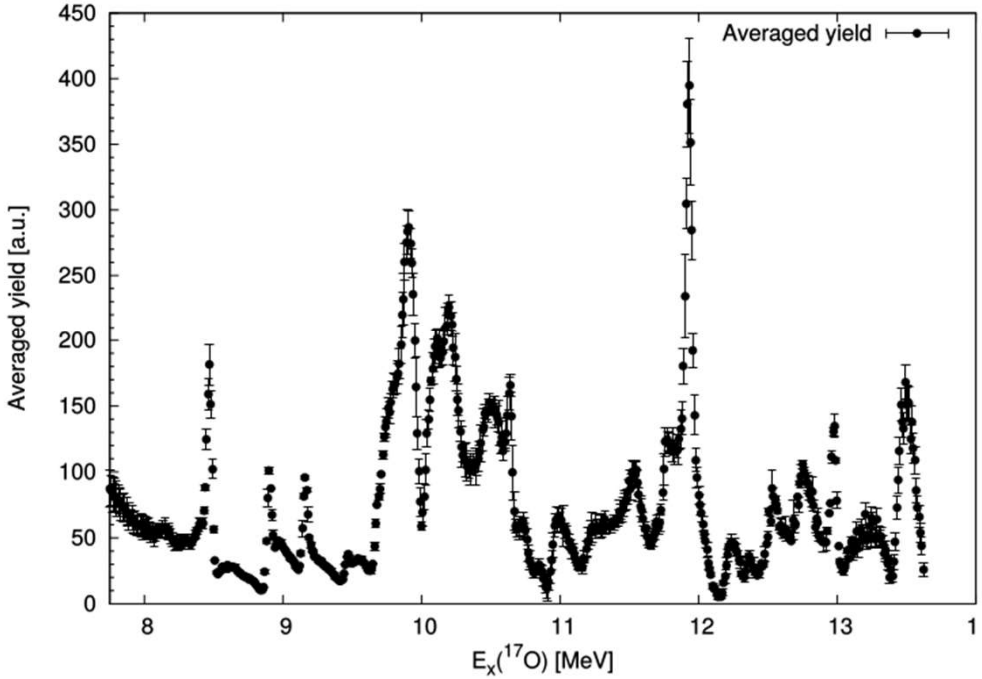
CM angle of scattered ^{4}He vs. $E_x(^{17}O)$
Assumed elastic scattering

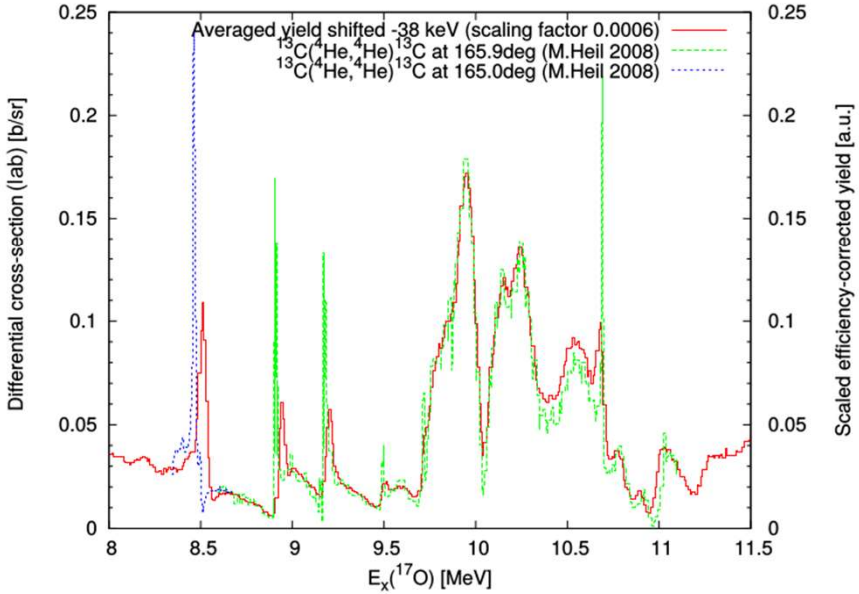
Further steps: detection efficiency correction (Θ_{CM} < 5 deg), normalization, data averaging for different runs



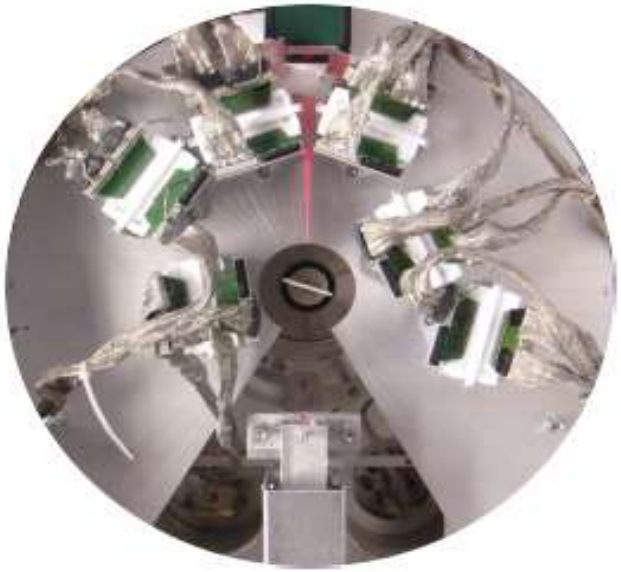
consistent sets of data,
inelastic contribution
negligible
our data at 175 deg

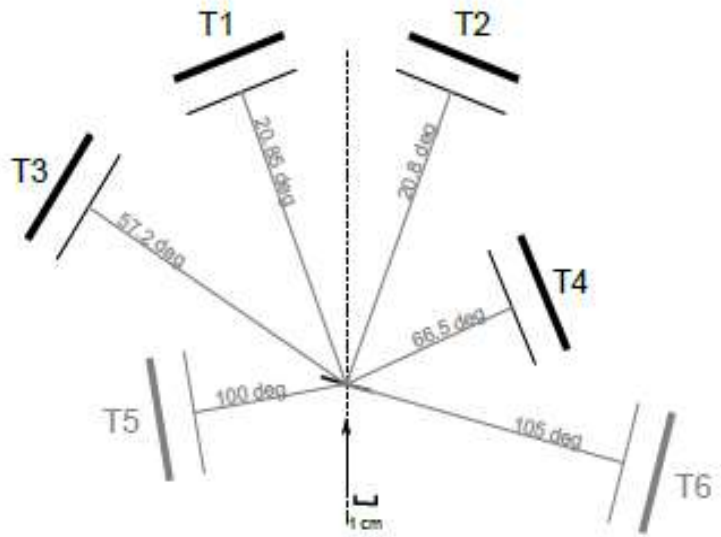
Published data: M Heil et al,
PRC 78 (2008) 025803,
up to excitation of 11.5 MeV





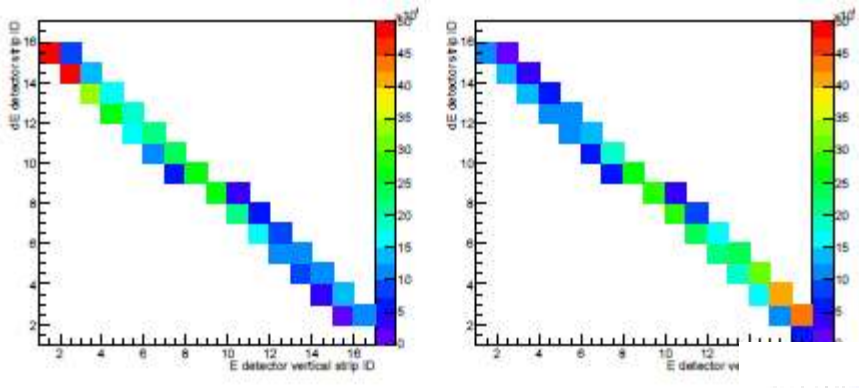
$E(^{13}C)_{beam}$=72 MeV, ^{9}Be target thickness 100 µg/cm^2
6 telescopes 20 µm SSSD + 1000 DSSSD µm, 50x50 mm^2
Micron Semiconductor type W1



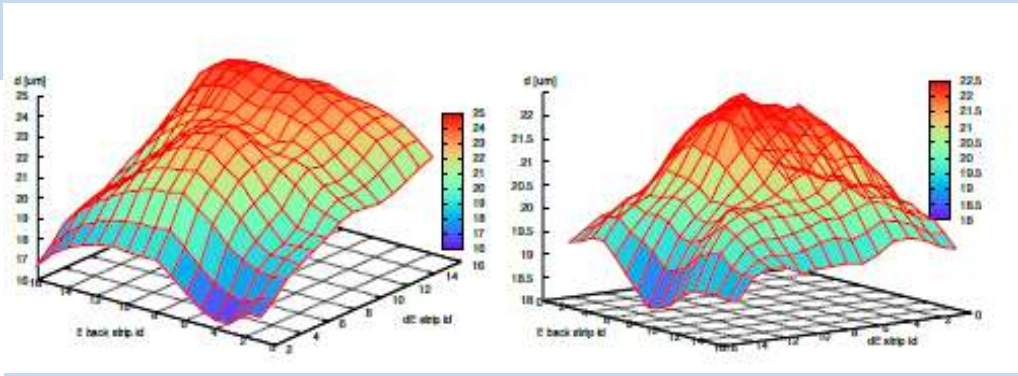


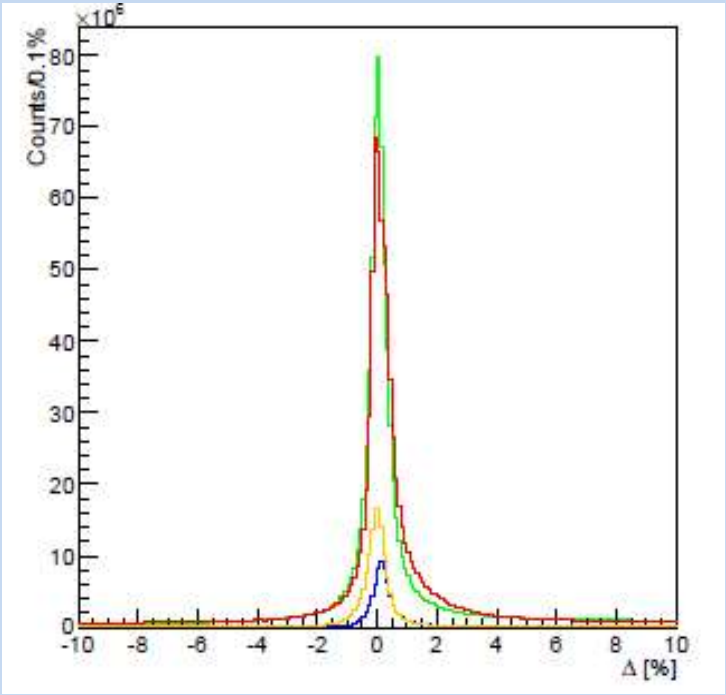
Detector telescope	$\vartheta_{min}^{in\ plane}$ [°]	$\vartheta_{max}^{in\ plane}$ [°]	$\Delta\vartheta$ [°]
T1	11.43	30.30	18.9
T2	11.38	30.24	18.9
T3	48.10	66.31	18.2
T4	52.48	80.53	28.1
T5	83.90	116.10	32.2
T6	95.49	114.76	18.8

The matching of the ΔE (vertical) strips to the E-detector vertical (front) strips



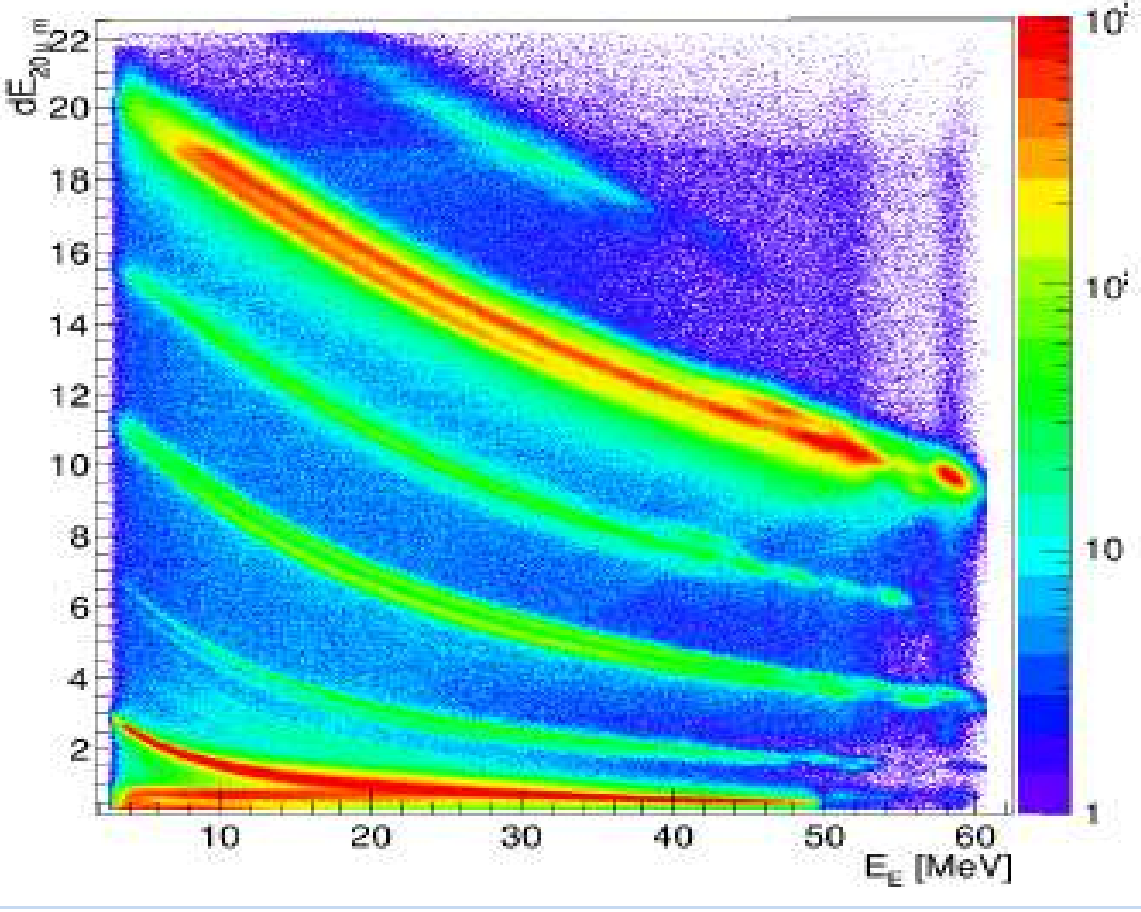
The ΔE-detector profiles for the T1 and T2.

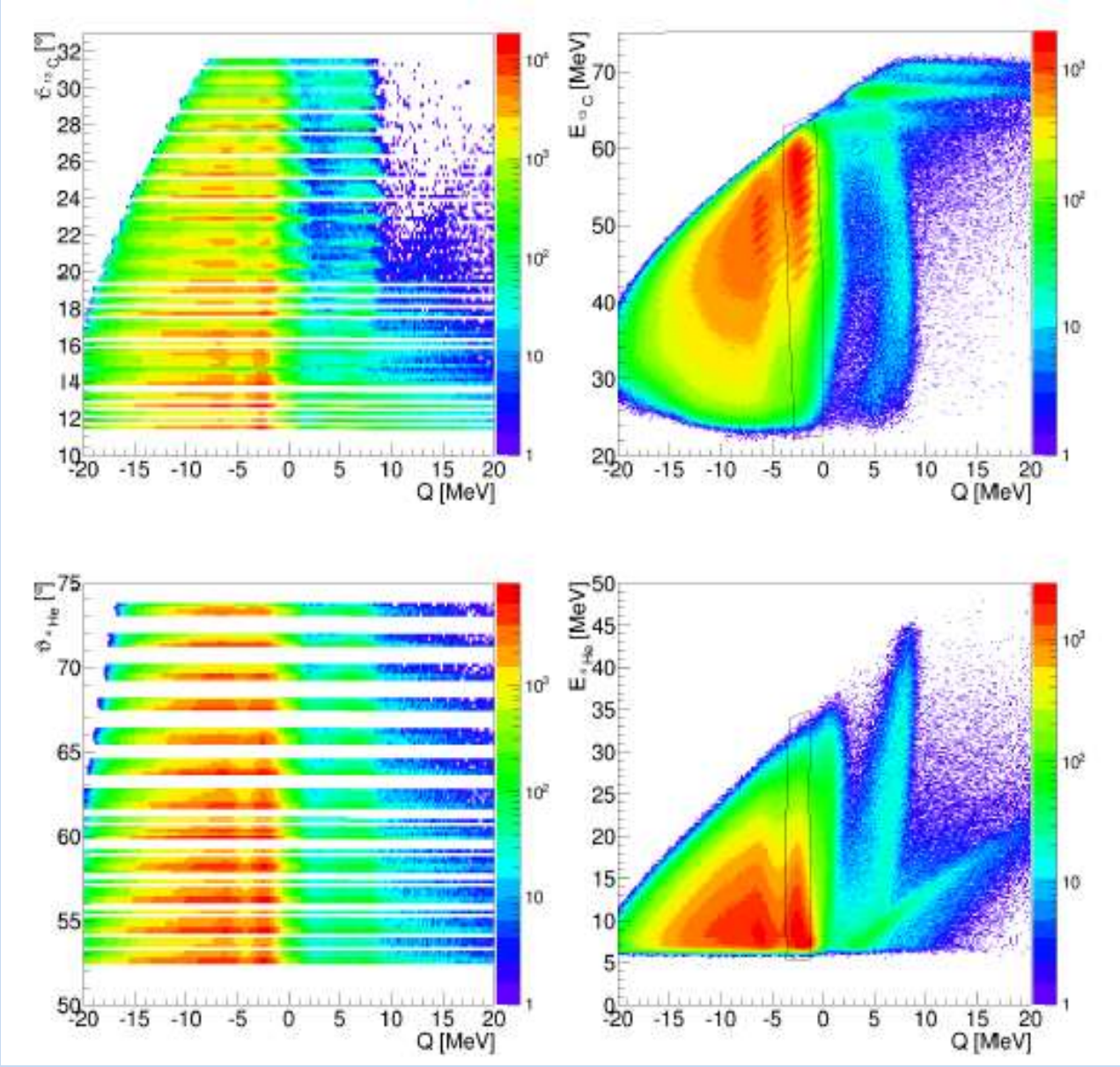




The front-strip vs back-strip energy difference relative to the average. Red line T1, green T2, blue T3, orange T4.

ΔE-E spectrum for the T1, ΔE-strip 13.





The Θ_{det}-Q and E^{det}-Q spectra for the $^{13}C(T1)$-$^{4}He(T4)$ coincident events. The black line denotes the graphical cuts used to select the ground state reaction channel.