Experimental results on $(sd)^3$ structures of ^{16}C and ^{17}C

Three-neutron $(sd)^3 \otimes$ core configurations

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Introduction

Ground state properties and first excited states of ^{16}C and ^{17}C

^{16}C: States of ^{16}C known up to 6.11 MeV excitation energy from the $^{14}C(t,p)$ reaction [Balamuth77, Fortune77, Sercely78]. Well described by shell model (SM) calculations. States up to 17.4 MeV observed in the $^{13}C(^{12}C,^{9}C)$ reaction [Boh03].

Ground state properties were investigated by one-neutron removal reactions using a ^{16}C radioactive beam [many refs., see, e.g., Maddalena01].
Result: 58(6) % $(1d5/2)^2$ and 42(6) % $(2s1/2)^2$ in good agreement with SM calculs.

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^{17}C: Only two states of ^{17}C observed in the ^{48}Ca(^{18}O,^{17}C)^{49}Ti reaction [Nolen77, Fifield82], the ground state and an excited state at 0.295(10) MeV (probably $5/2^+$).

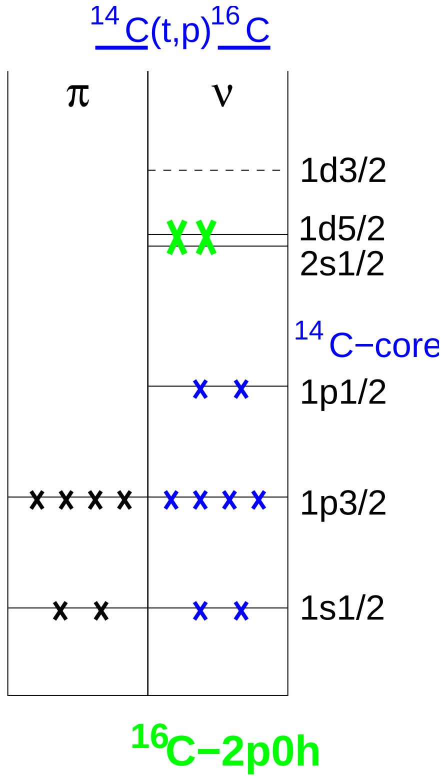
Puzzle: the spin-parity of the ^{17}C ground state: ?? $1/2^+$, $3/2^+$, $5/2^+$??
Solution: → $3/2^+$!!
a) β-decay of ^{17}C to exc. states of ^{17}N and γ-decay branching ratios:
   $5/2^+$ excluded [Warburton, Millener89].
b) g-factor measurement [Ogawa02]: $1/2^+$ excluded
c) ^{17}C-beam, 1n-removal cross sections confirm $3/2^+$ [Maddal.01, Sauvan04, Datta03]

Recently γ-transitions were reported at 0.21 MeV and 0.33 MeV [Stanoiu04]

Low-lying states of ^{16}C and ^{17}C:

^{16}C: ^{14}C(gs)$\otimes\nu$(sd)^2

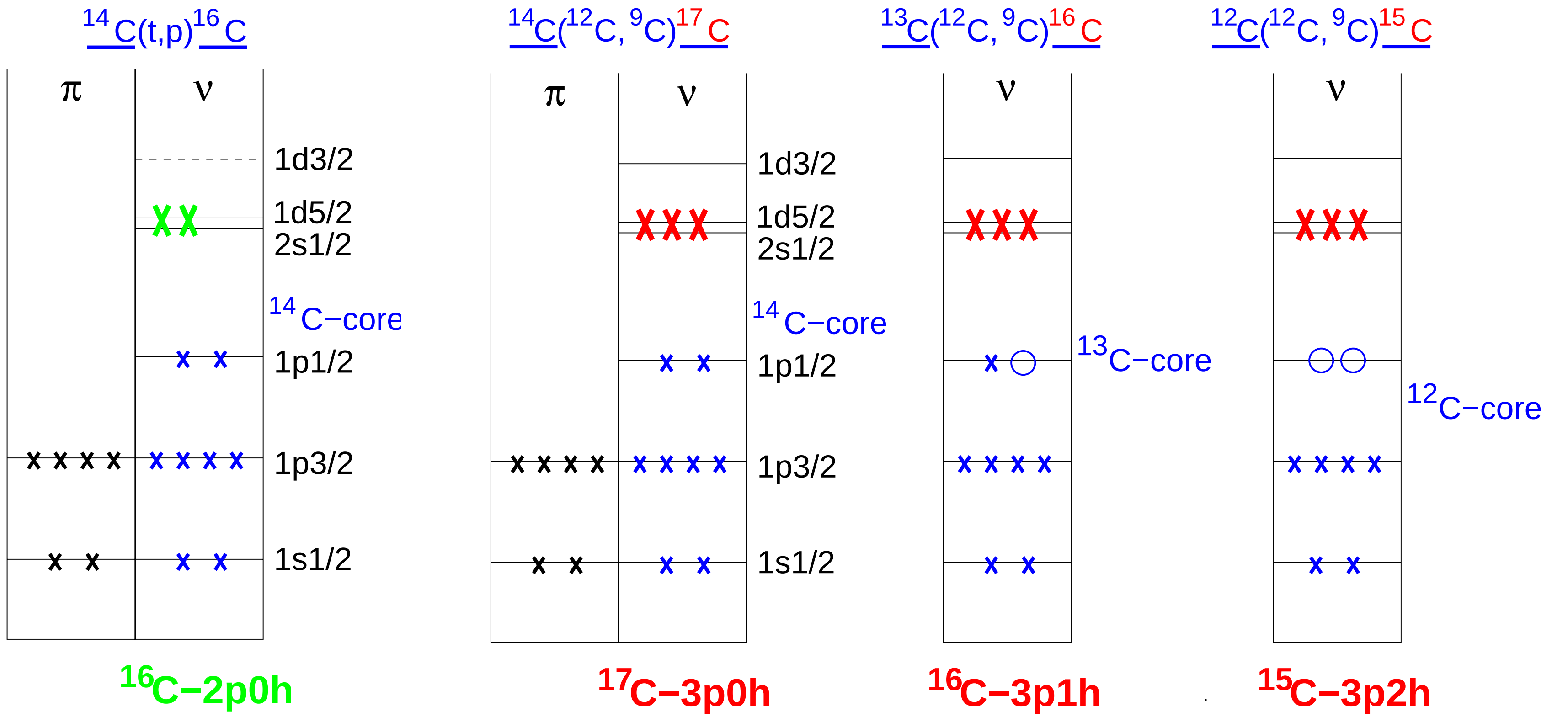
Schematic (sd)^2 :



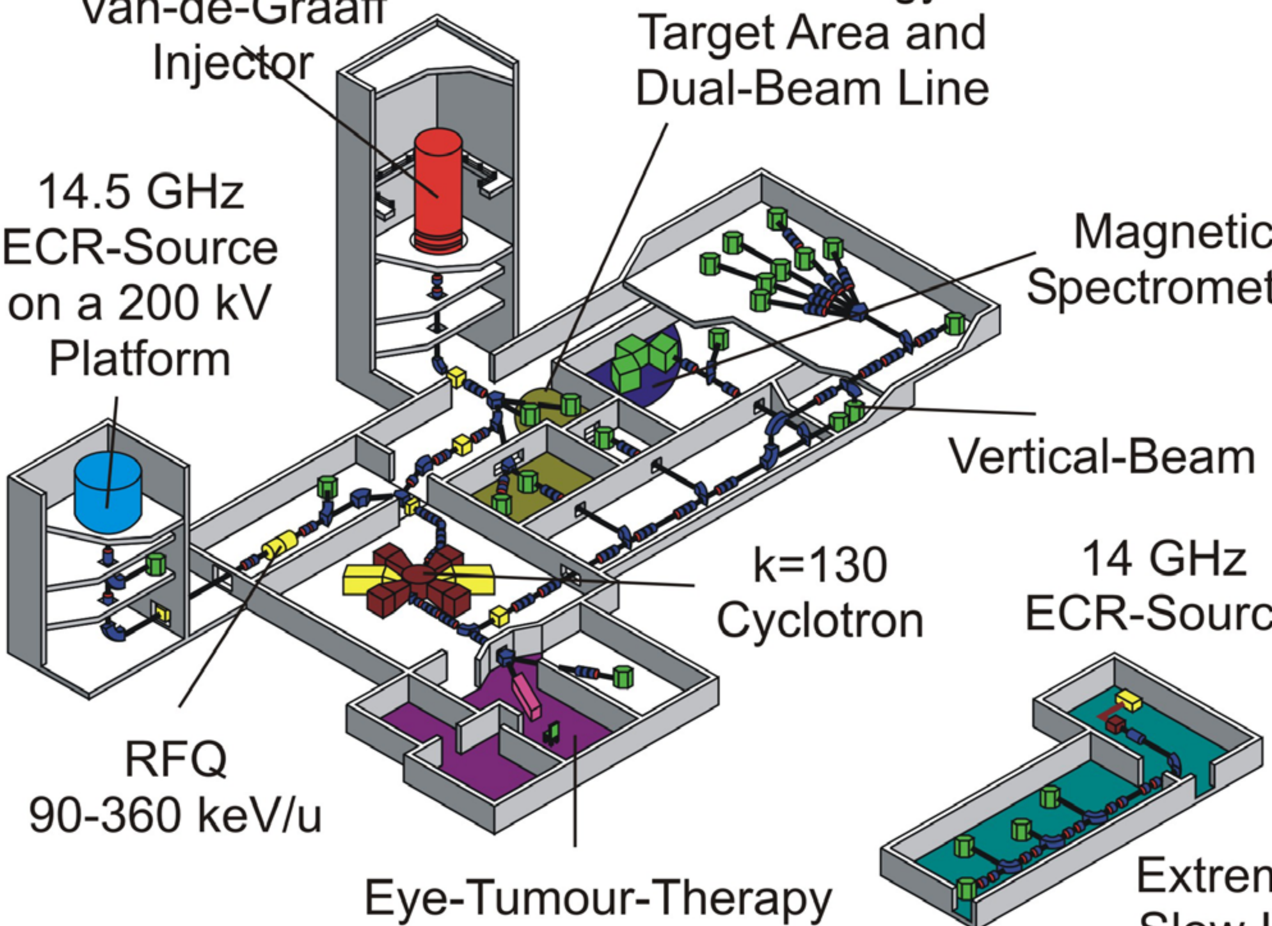
Low-lying states of ^{16}C and ^{17}C:

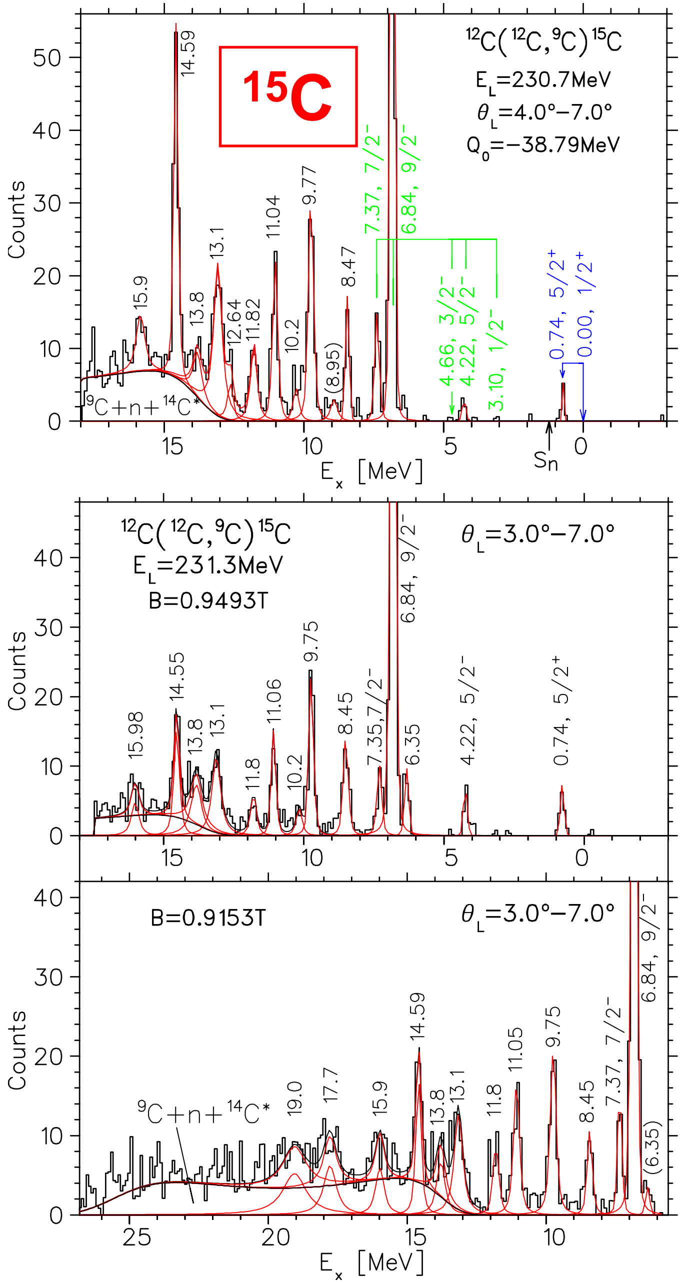
^{16}C: ^{14}C(gs)⊗ν(sd)^2 and **^{17}C, ^{16}C:** ^{14,13}C(gs)⊗ν(sd)^3, respectively.

Schematic (sd)^2 : (sd)^3 : direct population of three-neutron configurations



ISL at HMI Berlin



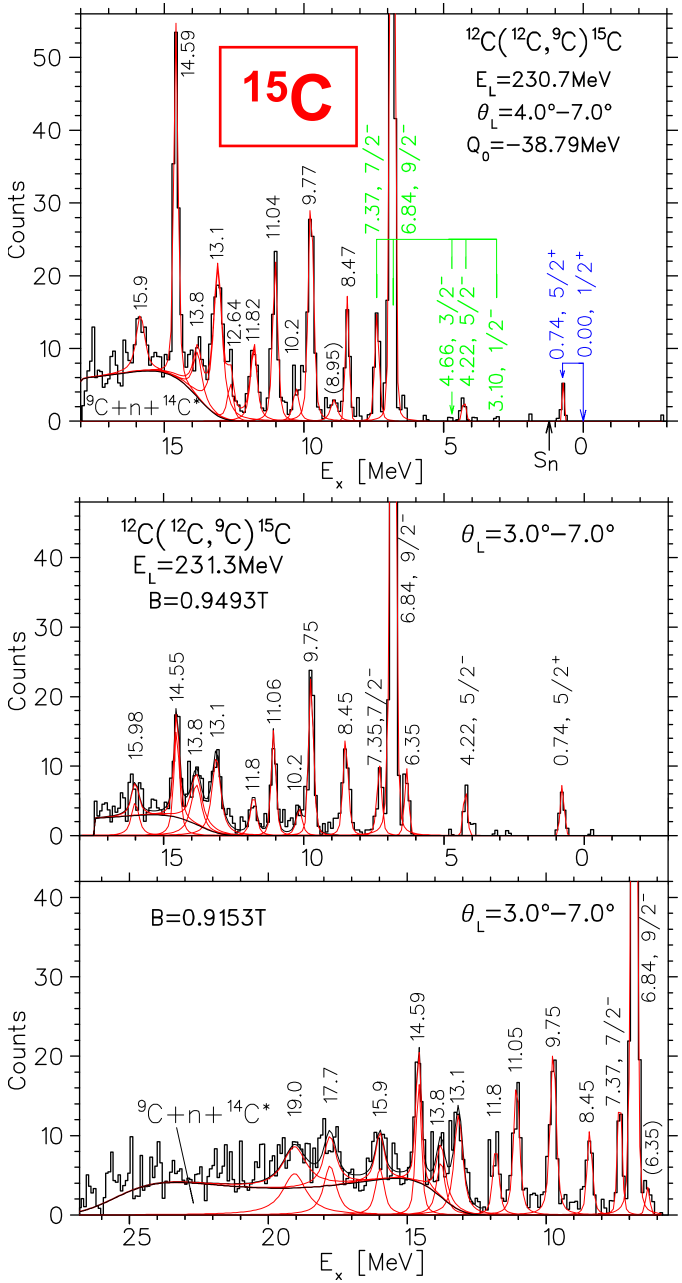


Reaction conditions and selectivity

The $^{12}C(^{12}C,^{9}C)^{15}C$ - reaction at 231 MeV

- Breit-Wigner resonances (S_n=1.22 MeV)
- Three-body distributions ^{9}C + n + $^{14}C^*$

sequential decay: $^{10}C^*$(22.2MeV) (3^{-}, 6.73MeV)



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- Cross sections are strongly dependent on dynamical matching conditions:

  large negative Q-values → extreme mismatch

  of grazing angular momenta: $L_{gr,i} - L_{gr,f} \geq 9$!

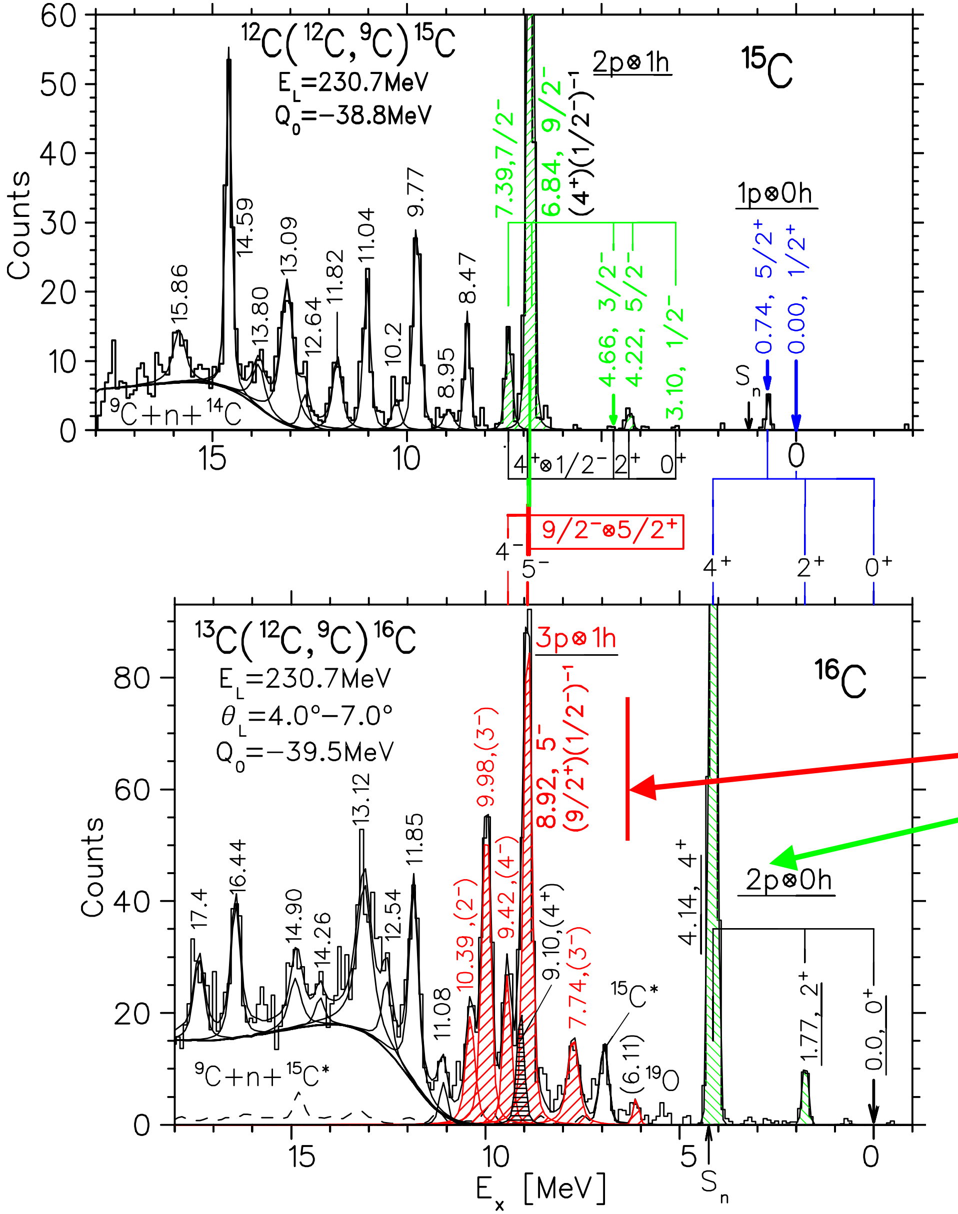
⟹ **stretched configurations are strongly favored**

e.g. $9/2^-$: $[(1d5/2)^2_{4+} \times (1p1/2)^{-1}]9/2^-$ yes (↑↑)

$7/2^-$: $[(1d5/2)^2_{4+} \times (1p1/2)^{-1}]7/2^-$ no (↑↓)

⟹ **ℓ=0 angular momenta are strongly disfavored**

Spectroscopy of ^{16}C using the three-neutron transfer (^{12}C,^{9}C)



^{15}C

(^{12}C-target, two holes in the 1p-shell)

energy resolution: 0.20 - 0.25 MeV

^{16}C:

(^{13}C-target, core with 1p1/2-hole built-in)

14 new states observed [Boh03]

states known from (t,p) [e.g., Fortune78]

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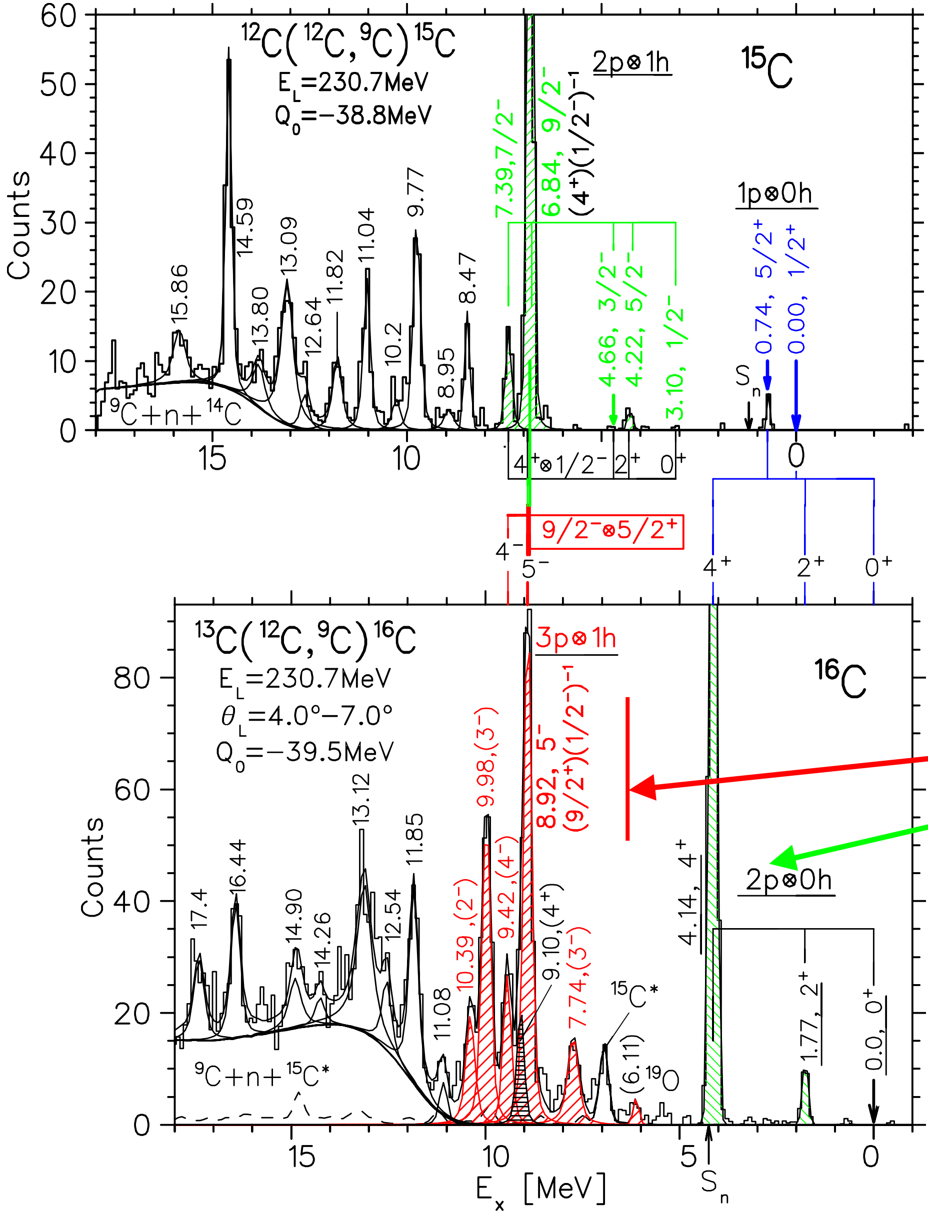

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known states

stretched configurations are ***strong:***

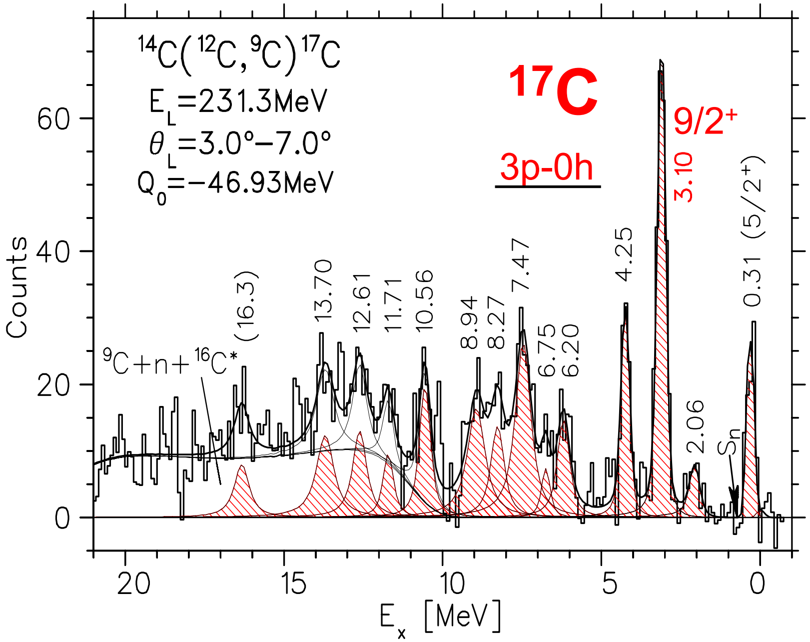
4^+ [$(1d5/2)^2$]

5^- [$(1d5/2)^3$,$9/2^+$ x $(1/2^-)^{-1}$]

5⁻,4⁻ doublet: $9/2^+$ (↑↑) $1/2^-$, $9/2^+$ (↑↓) $1/2^-$

3⁻,2⁻ doublet: $5/2^+$ (↑↑) $1/2^-$, $5/2^+$ (↑↓) $1/2^-$

Spectroscopy of ^{17}C



^{14}C-target, background subtracted

S_n= 0.73 MeV, Q_0= -46.93 MeV

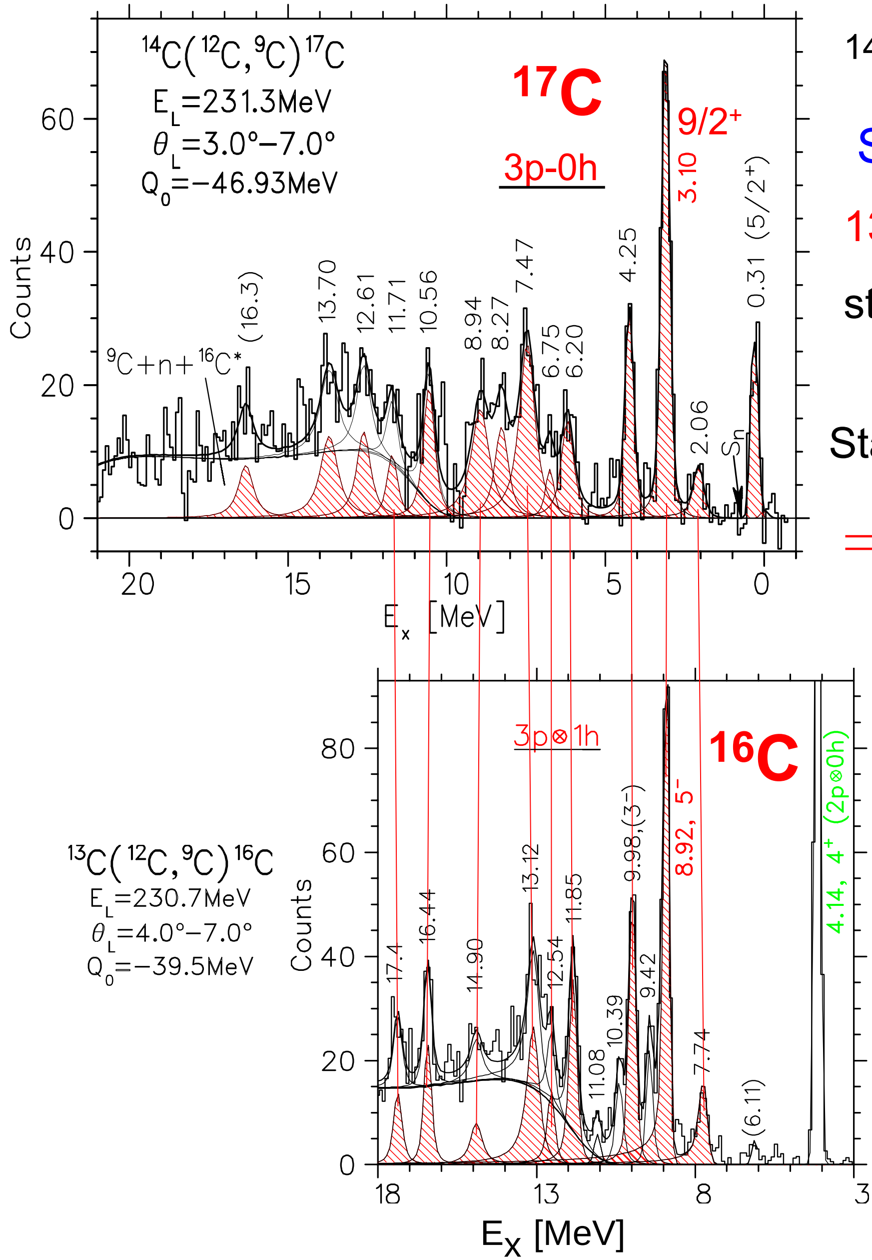
13 new states identified above S_n

strongest state: stretched config. $(1d5/2)^3 \rightarrow 9/2^+$

Starting with: $^{14}C_{gs}$ target (closed neutron 1p-shell)
direct 3n-transfer to the open sd-shell

$\Rightarrow$ population of $(sd)^3$ structures expected (3p-0h)

Spectroscopy of ^{17}C



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Comparison of ^{17}C - ^{16}C spectra

Spectra aligned for the states with $(1d5/2)^3$,$9/2^+$ configurations, in ^{16}C at 8.92 MeV and in ^{17}C at 3.10 MeV. (offset 5.82 MeV, same scale factor)

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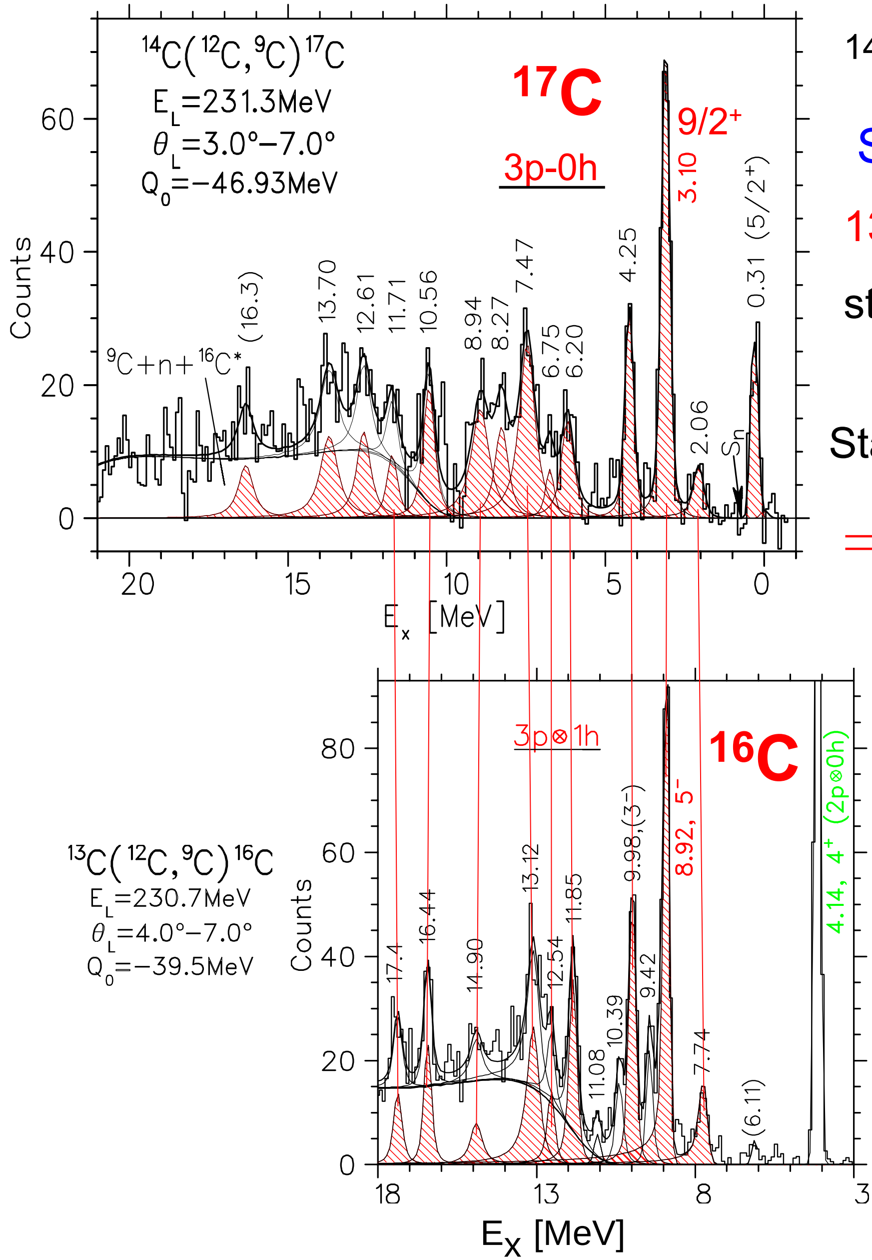

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Red lines are almost parallel !
connect states of corresponding structure
$\Rightarrow$ pairs of corresponding states

Comparison of observed excited states of ^{17}C and ^{16}C

State No.	2	3	4	5	6	7	8	9	10	11
$E_x(^{17}C)$ [MeV]	0.31	2.06	**3.10**	4.25	6.20	6.75	7.47	8.94	10.56	11.71

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$E_x(^{16}C)$ [MeV]	6.11[a]	7.74	**8.92**	9.98	11.85	12.54	13.12	14.90	16.44	17.4
$E_x(^{16}C)$ -**5.82**	0.29	1.92	**3.10**	4.16	6.03	6.72	7.30	9.08	10.62	11.58
$\Delta E_x(^{16}C^*,^{17}C)$	-0.02	-0.14	±0.0	-0.09	-0.17	-0.03	-0.17	+0.14	+0.06	-0.13

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reference from strongest states with streched configurations $[(5/2^+)^3]$ $9/2^+$

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$\Gamma(^{17}C)$ [MeV]	-	0.25	0.10	0.14	0.35	(0.20)	0.50	0.60	0.30	0.30
$\Gamma(^{16}C)$ [MeV]	<0.03[a]	0.20	≤0.10	0.12	0.22	(0.20)	0.40	0.30	0.15	0.15
$d\sigma(^{16}C)/d\sigma(^{17}C)$	-	2.9	2.0	2.9	3.3	3.0	1.7	0.6	1.3	1.6

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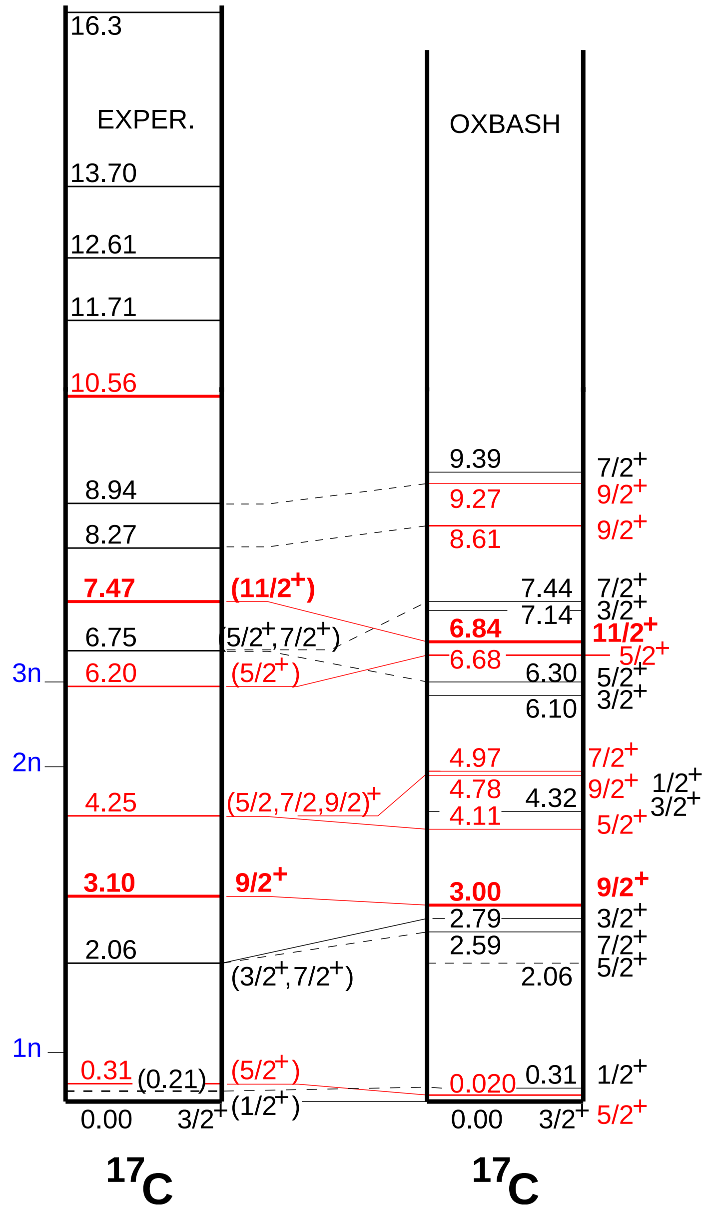
$d\sigma(^{16}C)/d\sigma(^{17}C)$	-	2.9	2.0	2.9	3.3	3.0	1.7	0.6	1.3	1.6

Conclusion: These pairs of corresponding states have a common 3n-structure. Direct population of $(sd)^3$ structures on ^{14}C, ^{13}C through the reaction mechanism. Change of the core changes the excitation energies only by a *global constant*.

Shell model calculations for ^{17}C



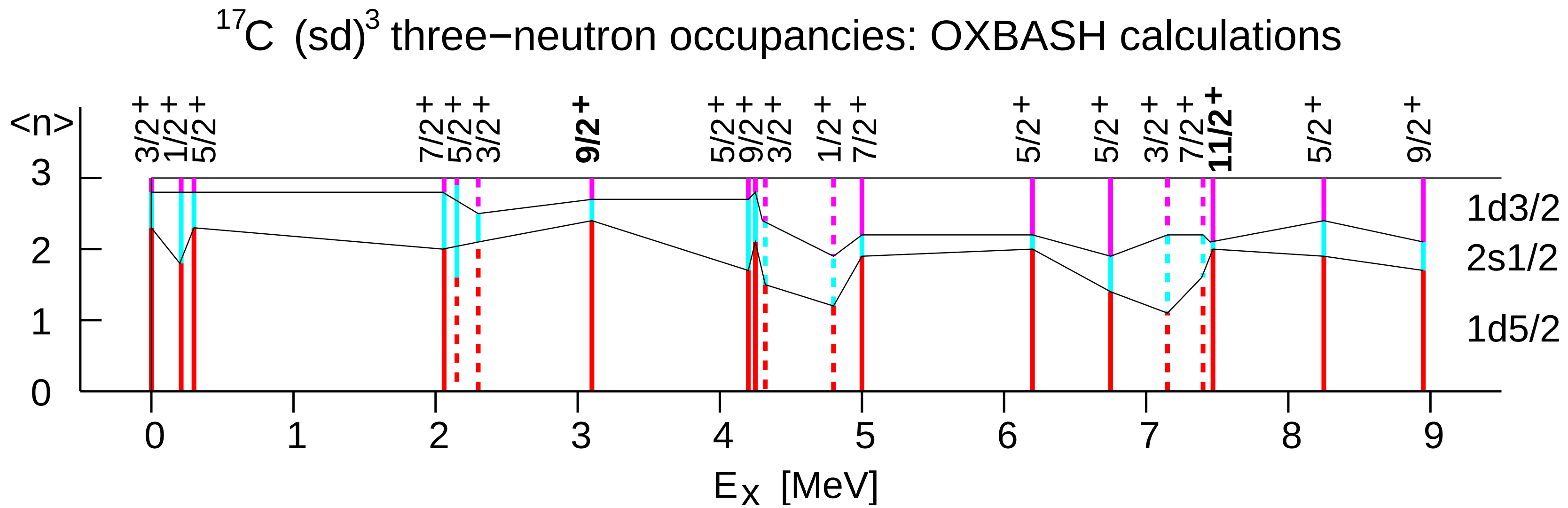
Code OXBASH
WBP interaction

<u>^{17}C model space:</u>

even-parity states

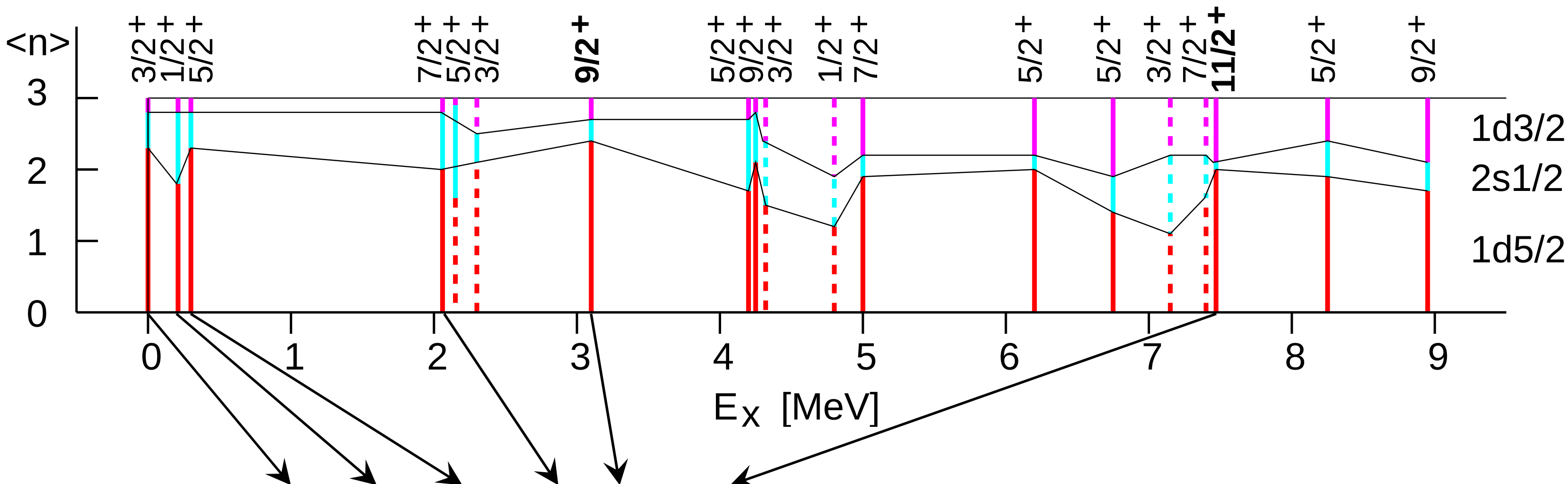
neutrons:
3 active neutrons in the (sd)-shell

4 active protons in the (psd)-shell, *proton 2^+ core excitation* was allowed, but the excitation needs 2^{nd} order process and more than 7 MeV extra excitation energy: small cross sections expected (these are not displayed here, all other states up to 9.5 MeV are shown).


^{17}C $(sd)^3$ three−neutron occupancies: OXBASH calculations
<n>
3/2+ 1/2+ 5/2+ 7/2+ 5/2+ 3/2+ 9/2+ 5/2+ 9/2+ 3/2+ 1/2+ 7/2+ 5/2+ 5/2+ 3/2+ 7/2+ 11/2+ 5/2+ 9/2+
1d3/2
2s1/2
1d5/2
0 1 2 3
0 1 2 3 4 5 6 7 8 9
E_X [MeV]

Shell model calculations for ^{17}C

^{17}C $(sd)^3$ three−neutron occupancies: OXBASH calculations

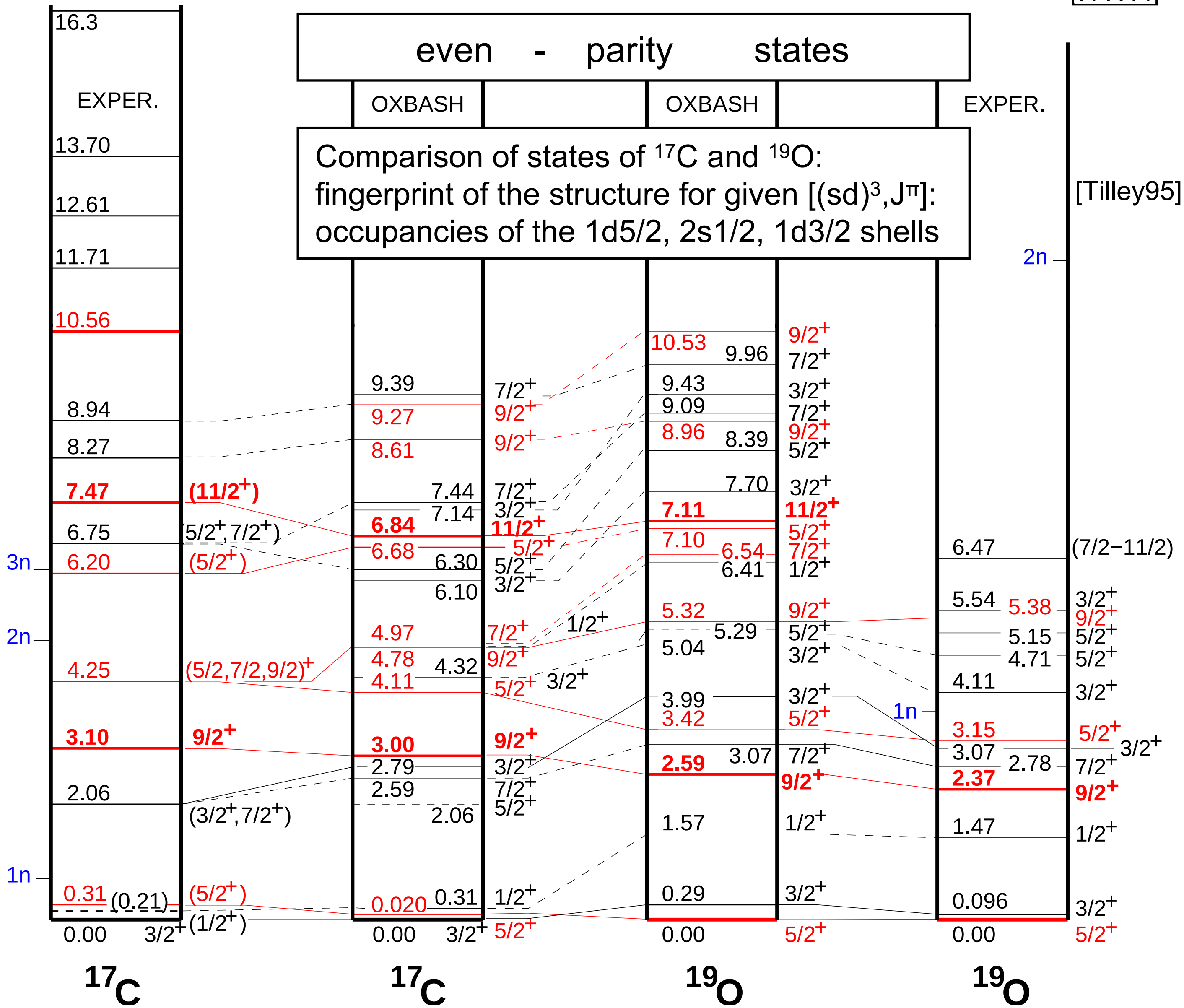


configurations	3/2 +	1/2 +	5/2 +	7/2 +	9/2 +	11/2 +
$(1d5/2)^3$	32%		47%		39%	
$(1d5/2)^2(2s1/2)^1$	31%	65%		65%	16%	
$(1d5/2)^2(1d3/2)^1$	2%		3%	3%	8%	68%
$(1d5/2)^1(2s1/2)^2$			19%			
$(1d5/2)^1(2s1/2)^1(1d3/2)^1$	6%	2%		7%	10%	
$(1d5/2)^1(1d3/2)^2$			5%			
$(2s1/2)^1(1d3/2)^2$		5%				
small components	9%	5%	6%	7%	3%	8%
$\pi(1p3/2)^3(1p1/2)^1$	10%	12%	9%	10%	13%	14%
$\pi(1p3/2)^2(1p1/2)^2$	10%	11%	10%	8%	11%	10%

Shell model calculations and comparison to ^{19}O

even - parity states

Comparison of states of ^{17}C and ^{19}O: fingerprint of the structure for given $[(sd)^3, J^\pi]$: occupancies of the 1d5/2, 2s1/2, 1d3/2 shells



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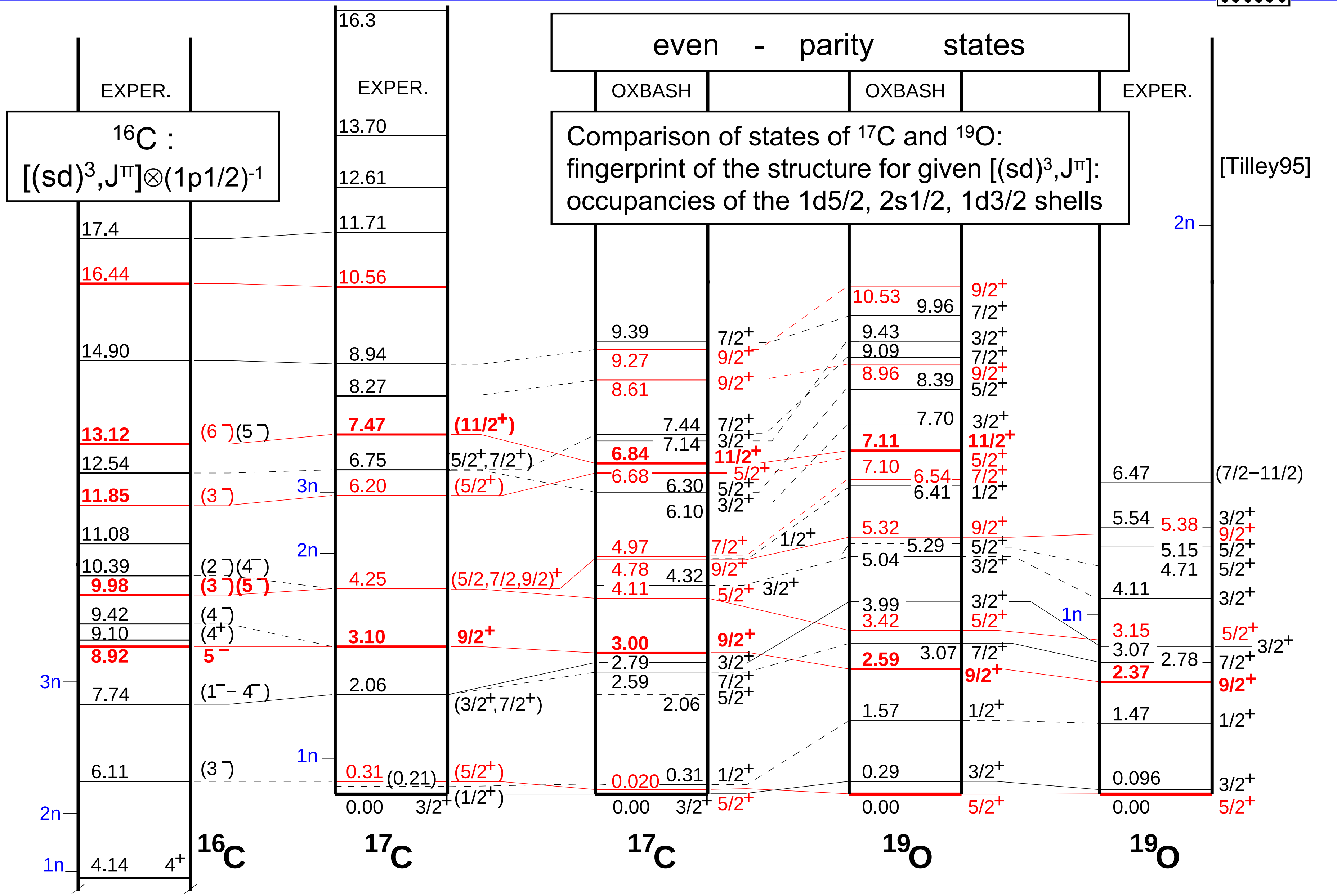
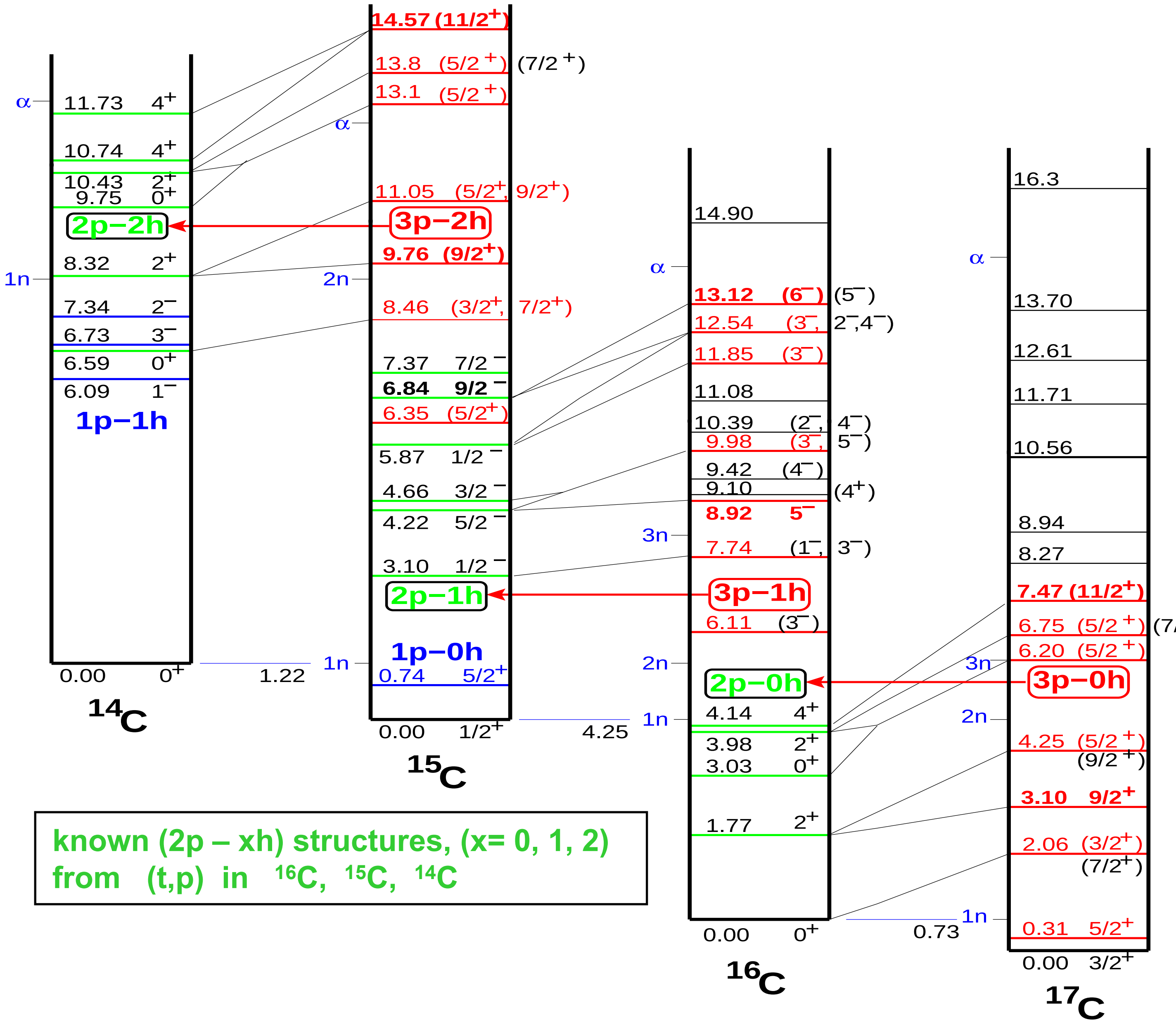


Decay properties, one-neutron decay



known (2p – xh) structures, (x= 0, 1, 2) from (t,p) in ^{16}C, ^{15}C, ^{14}C

Reduced decay energies :

$$E_{dec}=E_{x,i} - S_n - E_{x,f}$$

due to n-decay from (3p – xh) to (2p – xh) structures

$\Rightarrow \Gamma_{exp}(E_{dec})$

Spectroscopic information: reduced widths $\gamma^2_{\ell,exp}$

n-decay →

$$\Gamma_{exp} = 2\,\gamma^2_{\ell,exp}\,P_\ell(E_{dec})$$

^{17}C	E_x ^{17}C	E_x (MeV) → ^{16}C, J^π	E_{dec} (MeV)	Γ_{exp} (MeV)	$\gamma^2_{\ell,exp}$ (MeV) $\ell=0$	$\ell=2$
$(3/2^+)$	2.06	→ 0.00, 0^+	1.33	0.25	0.085	0.37
$9/2^+$	**3.10**	→ 1.77, 2^+	0.60	0.08	0.041	**0.55**
$(5/2^+,9/2^+)$	4.25	→ 1.77, 2^+	1.75	0.14	0.042	0.13
$(5/2^+)$	6.20	→ 3.03, 0^+	2.44	0.35	0.088	0.21
		→ 3.98, 2^+	1.49		0.110	0.43
$(5/2^+,7/2^+)$	6.75	→ 3.98, 2^+	2.04	(0.2)	0.055	0.15
$(11/2^+)$	**7.47**	→ 4.14, 4^+	2.60	0.50	0.120	**0.27**
^{16}C	^{16}C	→ ^{15}C, J^π				
$(1^- - 3^-)$	7.74	→ 3.10, $1/2^-$	0.39	0.15	0.094	2.69
5^-	**8.92**	→ 4.22, $5/2^-$	0.45	0.04	0.023	**0.52**
$(3^-, 5^-)$	9.98	→ 4.22, $5/2^-$	1.51	0.12	0.038	0.14
(3^-)	11.85	→ 5.87, $1/2^-$	1.73	0.22	0.066	0.21
(3^-)	12.54	→ 5.87, $1/2^-$	2.42	(0.2)	0.051	0.12
$(6^-, 5^-)$	**13.12**	→ 6.84, $9/2^-$	2.03	0.40	0.110	**0.30**

Summary and Conclusions

The structure and assignments of ^{17}C and ^{16}C *were discussed using the*

- ***dependence of cross sections*** *on* ***dynamical matching*** *conditions*
- ***striking similarity observed in the level schemes*** *of ^{16}C and ^{17}C,*

  indicating a common structure of $(sd)^3$ -type for corresp. pairs of states
- ***changing the core****, excitation energies change only by a global constant*
- ***shell model calculations for ^{17}C****, comparison to tentative assignments*
- ***comparison to ^{19}O*** *experimental levels and SM calculations*
- ***exper. widths*** *of resonances, decay properties,* ***reduced widths***

The neutron $(sd)^3$ excitation energies observed in ^{17}C and ^{16}C seem to be almost completely independent (within ±0.16 MeV) from the corresponding cores ^{14}C,^{13}C, respectively, except a global constant. This is found for 10 pairs of states for ^{17}C,^{16}C over a range of 10MeV excitation energy.