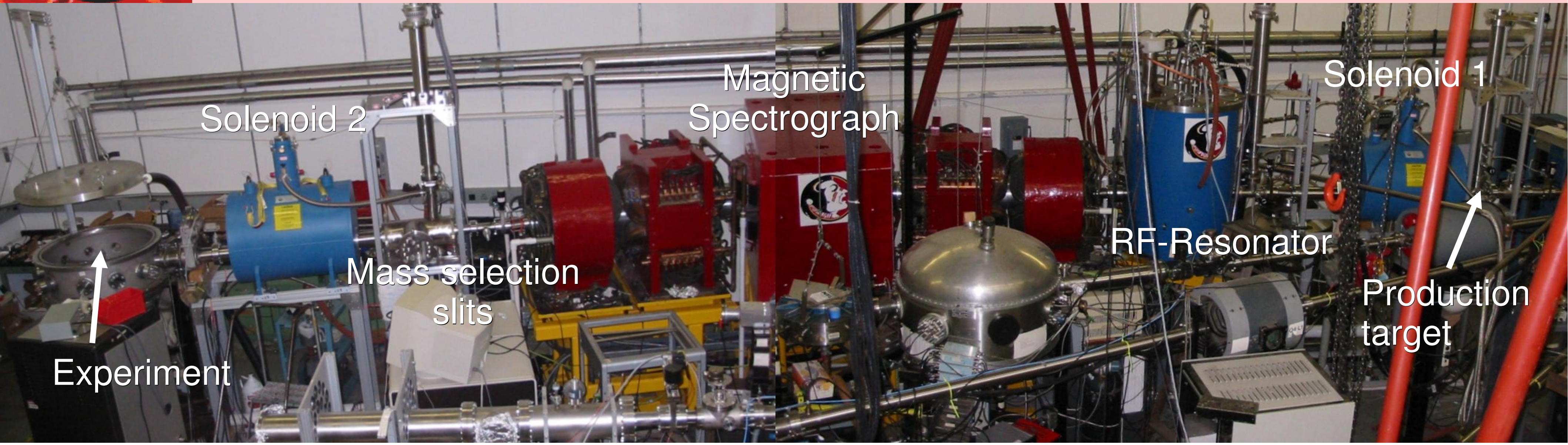
Spectroscopy of light exotic nuclei using resonance scattering in inverse kinematics.

Grigory Rogachev

RESOLUT: a new radioactive beam facility at FSU



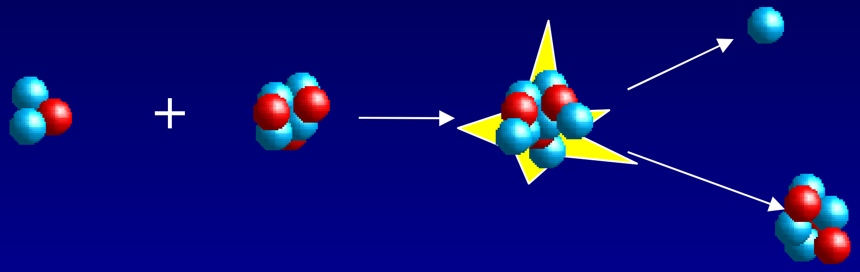
- In-flight production of radioactive beams in inverse kinematics
- Combination of Superconducting RF-Resonator with high acceptance magnetic Spectrograph to create mass spectrometer

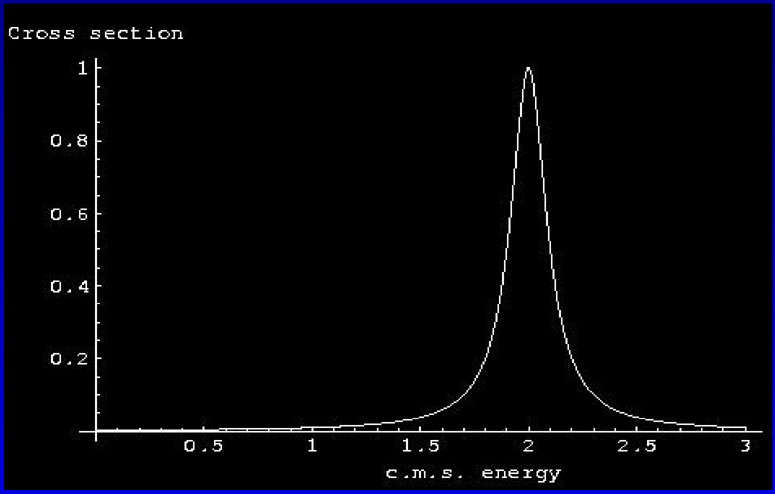
Light exotic nuclei are perfect proving grounds for modern theoretical approaches.

- How well the "ab initio" approach (tuned for stable nuclei) describes the properties of exotic nuclei?
- For weakly bound (or unbound) light exotic nuclei even the ground state can already be in continuum, providing great opportunity to study continuum coupling effect in a framework of Continuum or Gamov Shell Model.

Resonance reactions with radioactive beams provide direct access to unbound states in exotic nuclei.

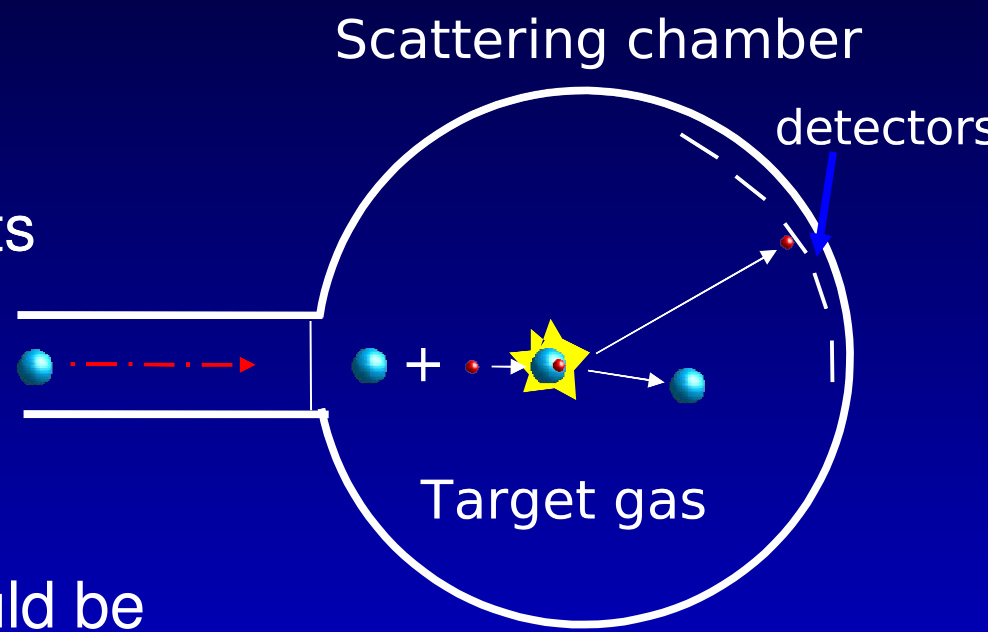
- Large cross section.
- Clear understanding of the process.
- Direct, model independent measure of the "spectroscopic factors". Width -> SF





Thick Target Inverse Kinematics (TTIK) technique

- High efficiency
- Good energy resolution
- 180° (c.m.s.) measurements are possible
- Excitation function is continuous
- Low excitation energies could be measured due to energy amplification in inverse kinematic



Thick target -> High efficiency
Recoil energy losses are low -> Good energy resolution

Spectroscopy of light exotic nuclei using resonance scattering in inverse kinematics.

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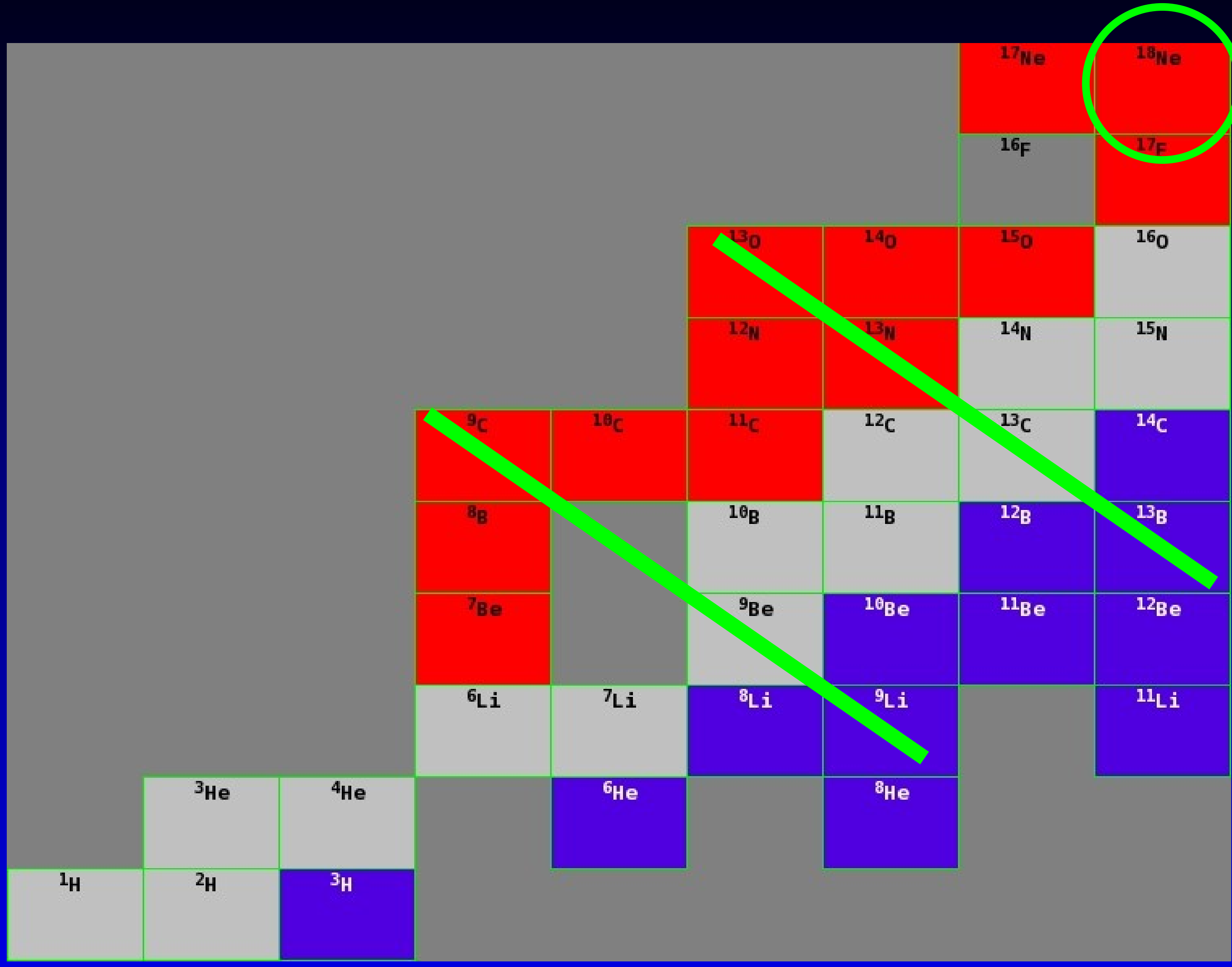
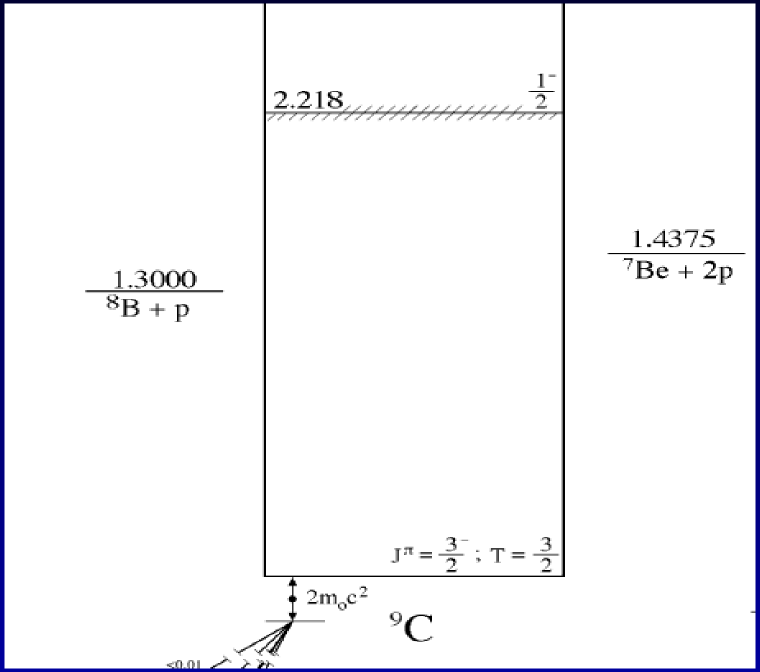
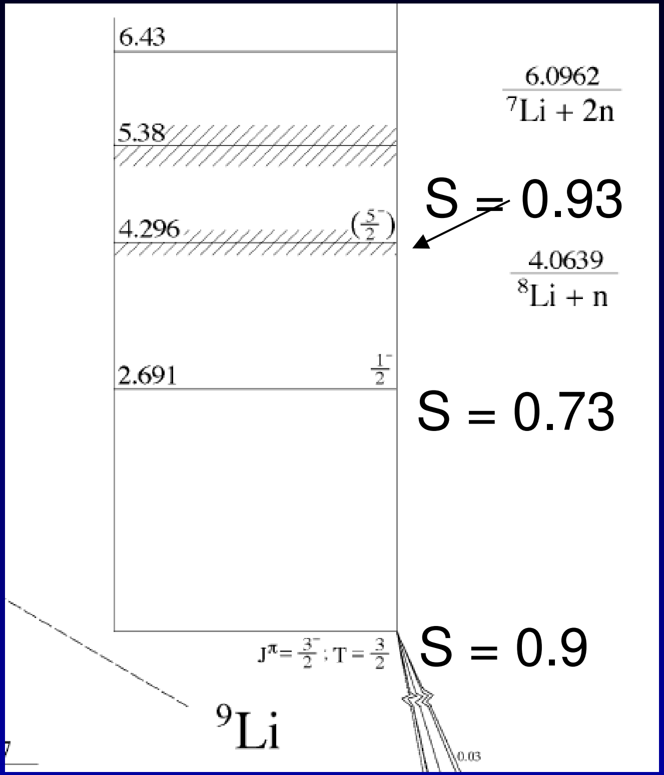


Structure of ^9C



D.R. Tilley et al., NPA 745 (2004) 155.

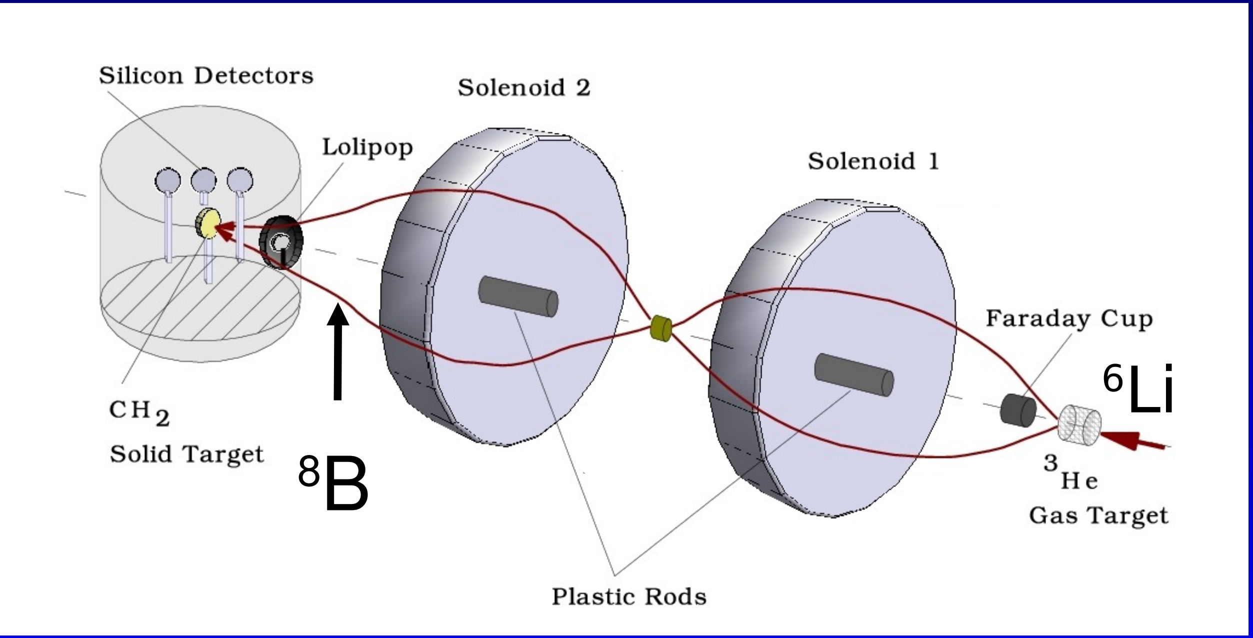


Spectroscopic factors are from A.H. Wuosmaa PRL 94, 082502 (2005)

- All spectroscopy information about ^9C comes from $^{12}C(^3He,^6He)^9C$ reaction.
- Only the ground and the first excited states were observed.

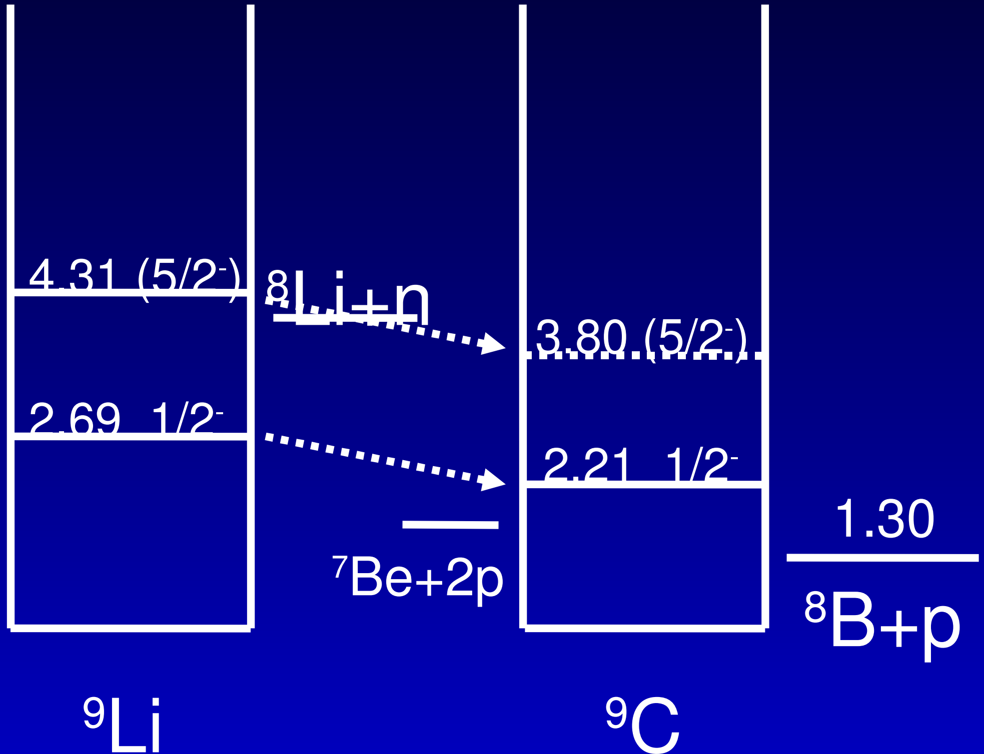
Structure of ^{9}C

- Resonances in ^{8}B+p system reveal states in ^{9}C starting from the first excited state.
- University of Notre Dame TWINSOL RNB facility was used to produce ^{8}B beam from 39 MeV ^{6}Li beam.
- ^{8}B beam was produced using ^{3}He(^{6}Li,^{8}B)n with energy of 30 MeV.

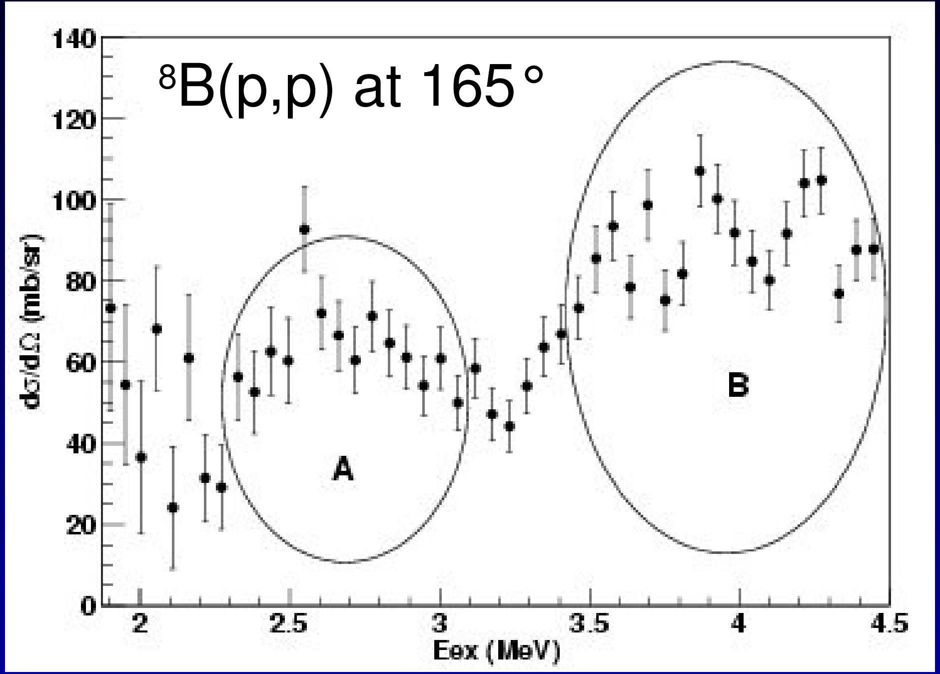


Structure of ^9C

What we would expect to see?

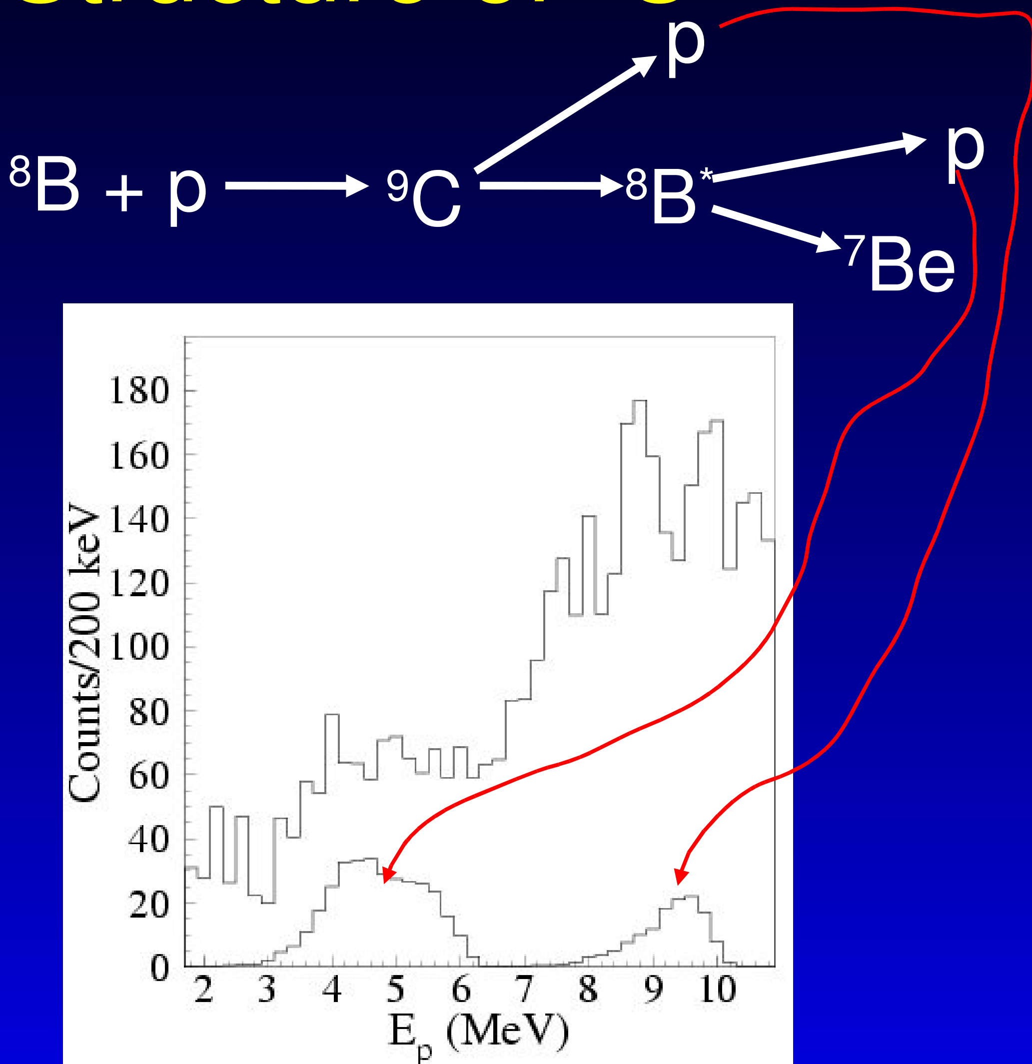


Nollen-Schiffer effect was estimated using Woods-Saxon potential, by fitting excitation energies in ^9Li



- Feature B can be associated with 5/2- state.
- Feature A escapes simple explanation.

Structure of ^{9}C



- Experiment cannot distinguish between elastic and inelastic process.
- Inelastic process produces TWO protons.
- Proton produced in decay of the first excited state of ^{8}B shows up as a broad peak at 5 MeV.

Structure of ^{9}C: CSM results

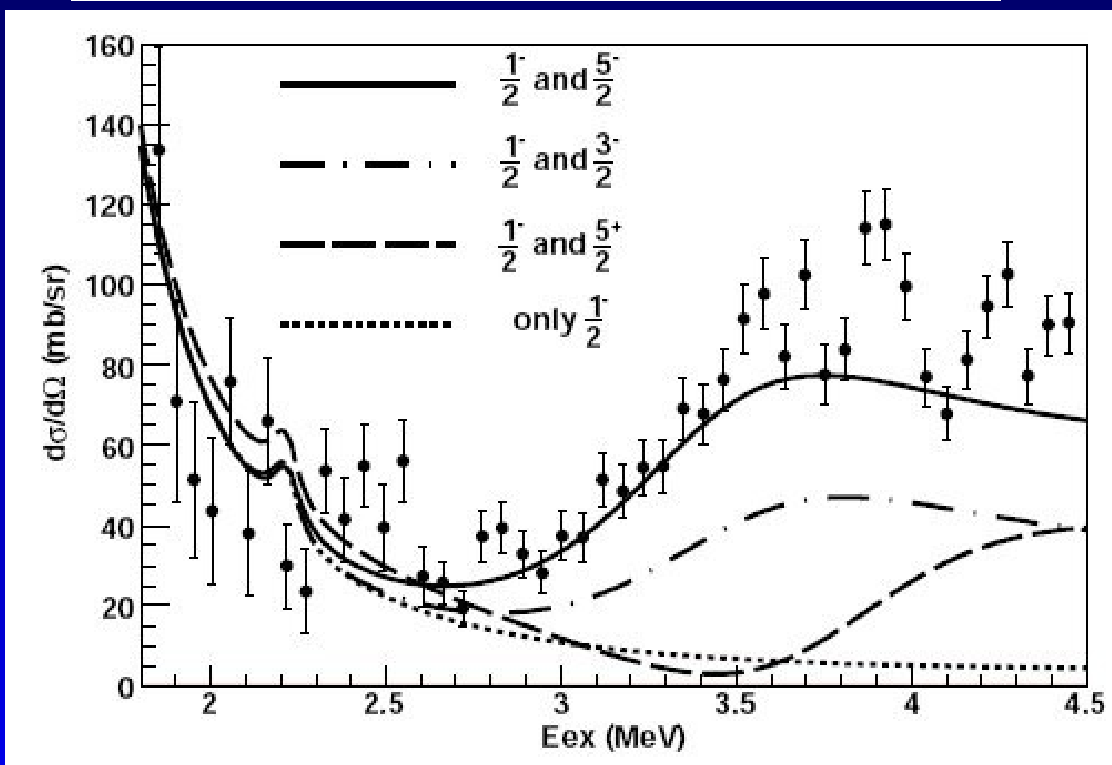
Table I: Continuum Shell Model results for ^{9}C performed with the WBP interaction [10] in an s-p-sd-pf valence space. Calculated excitation energies, widths, spectroscopic factors and eigenstate reorientation angles are given for the first five states in ^{9}C. The known experimental value for the excitation energy of the $1/2^-$ state [12] and the excitation energy of the $5/2^-$ state measured in this work were used in the reaction calculations.

J^π	E_{th} (MeV)	E_{exp} (MeV)	Γ (MeV)	Θ deg	$\psi_p \otimes \psi_{^8B(gs)}$ $S(p_{3/2})$	$S(p_{1/2})$	Γ_{WS}	$\psi_p \otimes \psi_{^8B(1^+)}$ $S(p_{3/2})$	$S(p_{1/2})$	Γ_{WS}
$3/2^-$	0.00	0.00	0.000	0.0	0.87	0.00	0.0	0.18	0.00	0.0
$1/2^-$	1.4	2.2	0.027	0.1	0.18	0.00	0.15	0.75	0.00	7.6E-3
$5/2^-$	3.9	3.6	1.30	5.1	0.13	0.59	1.80	0.00	0.00	0.59
$3/2^-$	4.1	-	1.32	10.8	0.08	0.09	3.19	0.23	0.47	1.14
				$S(d_{5/2})$	$S(d_{3/2})$	$S(s_{1/2})$	$S(d_{5/2})$	$S(d_{3/2})$	$S(s_{1/2})$	
$3/2^+$	4.2	-	2.1	16.0	0.00	0.01	0.41	0.05	0.002	0.03

- Excitation energies and widths were calculated.
- Angle Θ measures effects of the continuum on the resonance wavefunction.
- Spectroscopic factors are calculated as overlap integrals between the SM wavefunctions (no continuum).

Structure of ^{9}C.

$$\gamma_{\lambda c} = \left(\frac{\hbar^2}{\mu_c a_c^2}\right)^{\frac{1}{2}} \sum_j A_{\lambda c j} (-1)^{I_1+I_2+\ell+J} \sqrt{2S+1}\sqrt{2j+1} \begin{Bmatrix} I_1 & I_2 & S \\ \ell & J & j \end{Bmatrix},$$

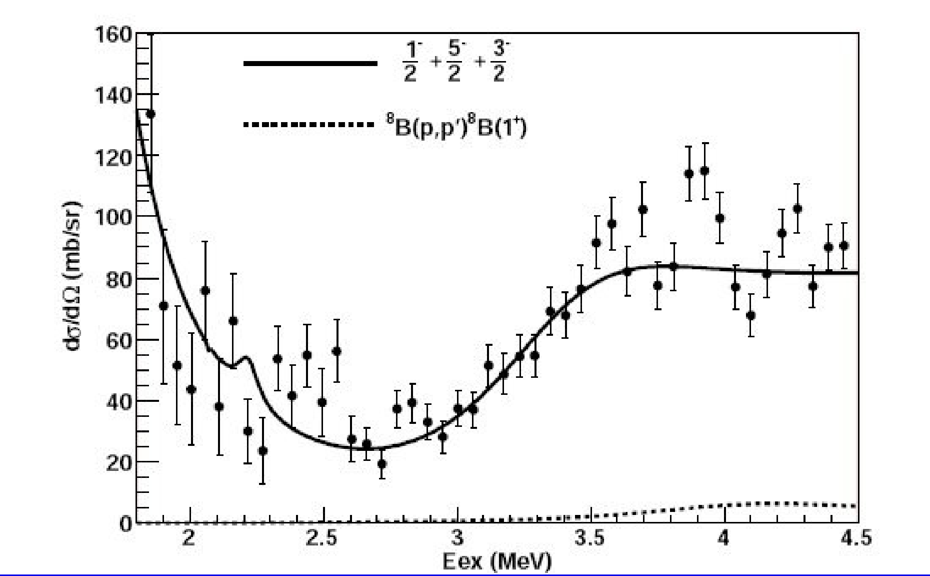


- Reduced width was first calculated from CSM spectroscopic amplitudes.
- $5/2^-$ predicted by CSM describes the observed excitation function.
- No other spin parity assignment is consistent with the data.

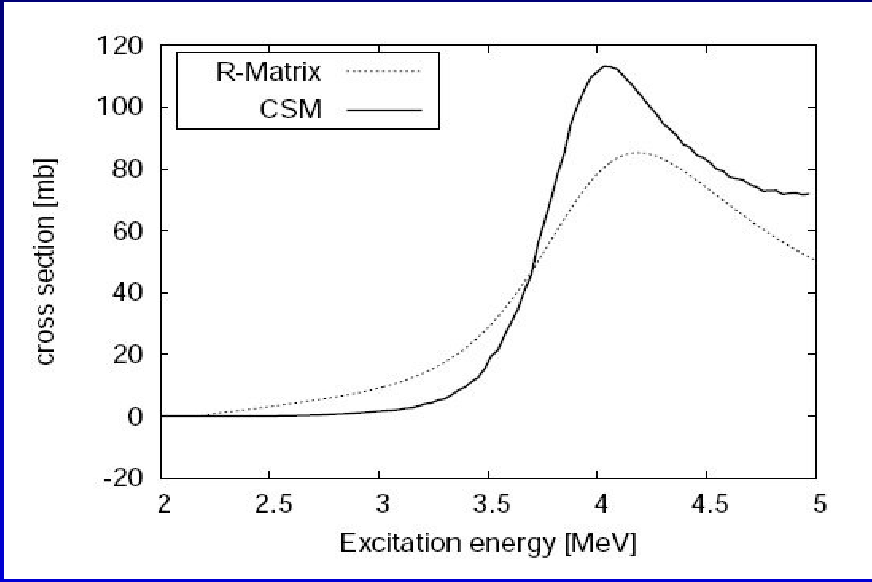
Structure of ^{9}C.

Table III: Excitation energies, energy eigenvalues, widths and reduced-width amplitudes of the resonances in ^{9}C.

J^π	ℓ	S	B_c	$\frac{1}{2}^-$	$\frac{5}{2}^-$	$\frac{3}{2}^-$
E_x (MeV)				2.22	3.6	4.1
E_λ (MeV)				0.61	3.45	4.15
Γ (MeV)				0.10	1.4	1.3
p+^{8}B(g.s.)	1	$\frac{3}{2}$	-1.2	1.15 (0.65)	0.33 (0.47)	0.17 (0.17)
	1	$\frac{5}{2}$	-1.2	-	-1.34 (-1.20)	0.59 (0.59)
p+^{8}B(1$^+$)	1	$\frac{1}{2}$	-1.2	1.25 (1.25)	-	-0.15 (-0.15)
	1	$\frac{3}{2}$	-1.2	0.42 (0.42)	0.00 (0.00)	1.27 (1.27)



- Good fit and high inelastic cross section can be obtained if 3/2$^-$ is introduced.



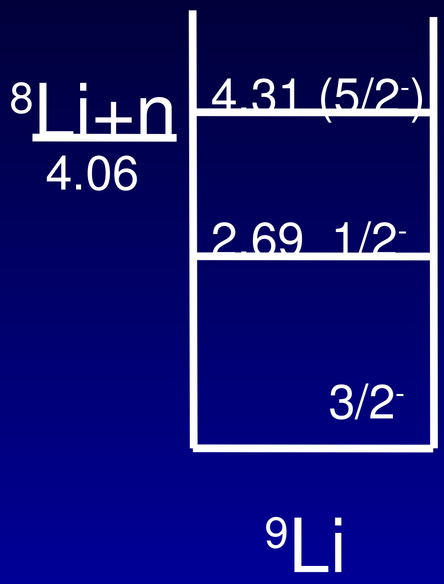
Total inelastic cross section

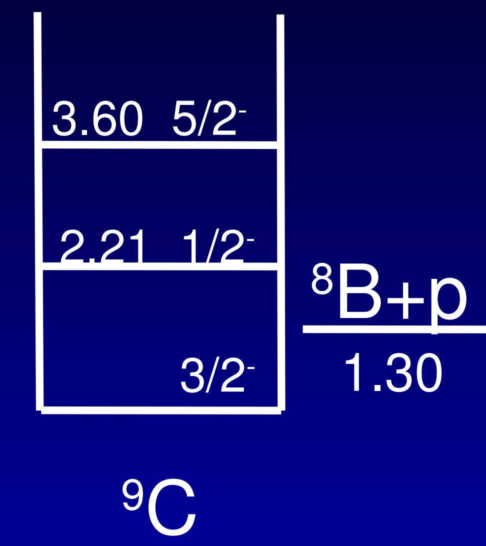
Structure of ^{9}C.

- The new state, $5/2^{-}$, was observed at 3.6 MeV with width of 1.3 MeV. Comparison to the CSM indicates the SF 0.72. This is in agreement with all *ab initio* models, with CSM predictions, and with recent experimental result of Wuosmaa et al., PRL (2005) on the SF of states in ^{9}Li. No other spin-parity assignment for the state is consistent with the experimental data.
- An indication on the presence of state(s) above 4.0 MeV with large inelastic component was observed. A good candidate is $3/2^{-}$ state.
- CSM was essential part of the analysis and seems to describe the properties of the low lying states in ^{9}C very well.

G.V. Rogachev, et al., PRC 75 (2007) 014603

T=3/2 states in A=9 isobaric chain.



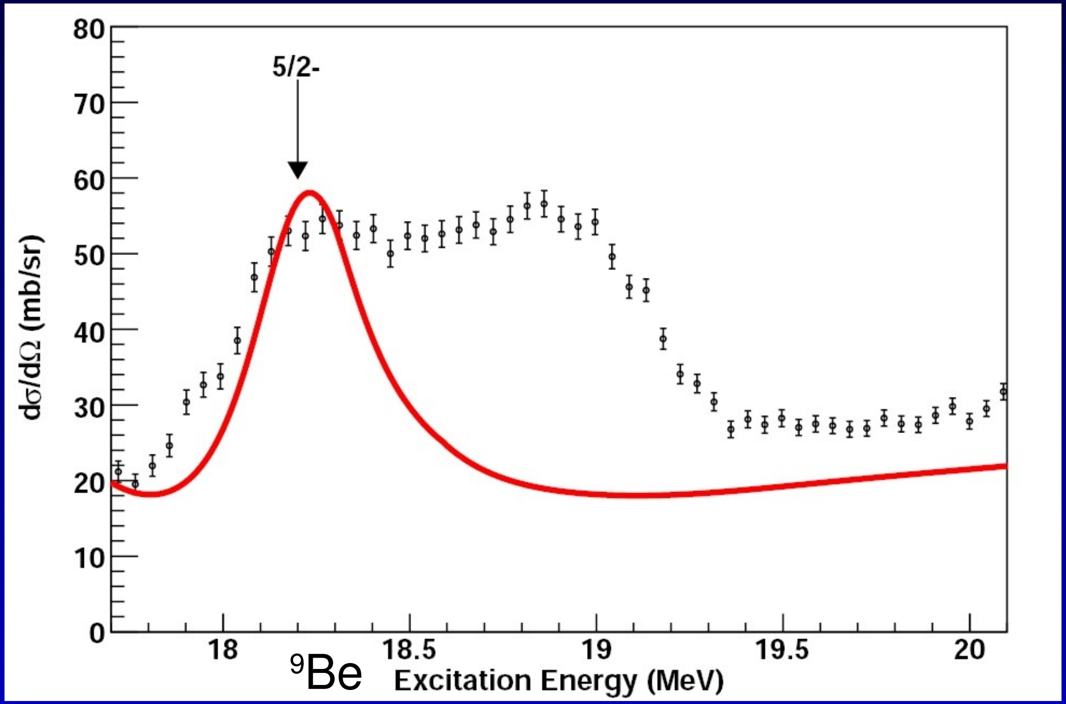


^{8}Li+p elastic scattering can be used to populate T=3/2 resonances in ^{9}Be.

Important: neutron decay of T=3/2 resonances in ^{9}Be to T=0 states in ^{8}Be is isospin forbidden.

Isobaric analogs in ^{9}Be. (T=3/2)

^{8}Li+p->^{9}Be(T=3/2)->^{8}Li+p

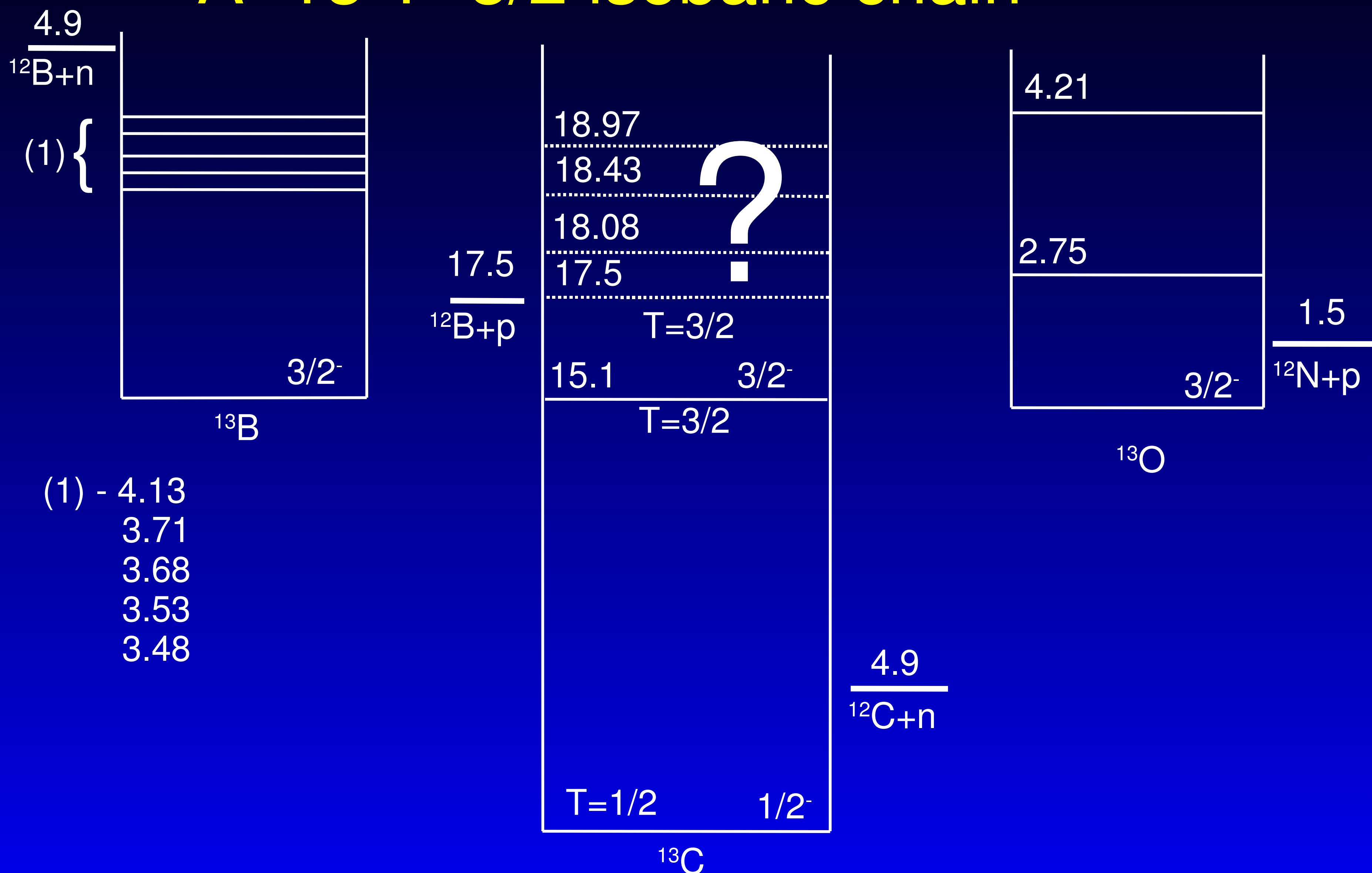


- Large cross section at 18-19 MeV suggests more than one T=3/2 state in this region.
- Analysis is in progress.

The ^{8}Li+p excitation function measured at 164 degrees in c.m.

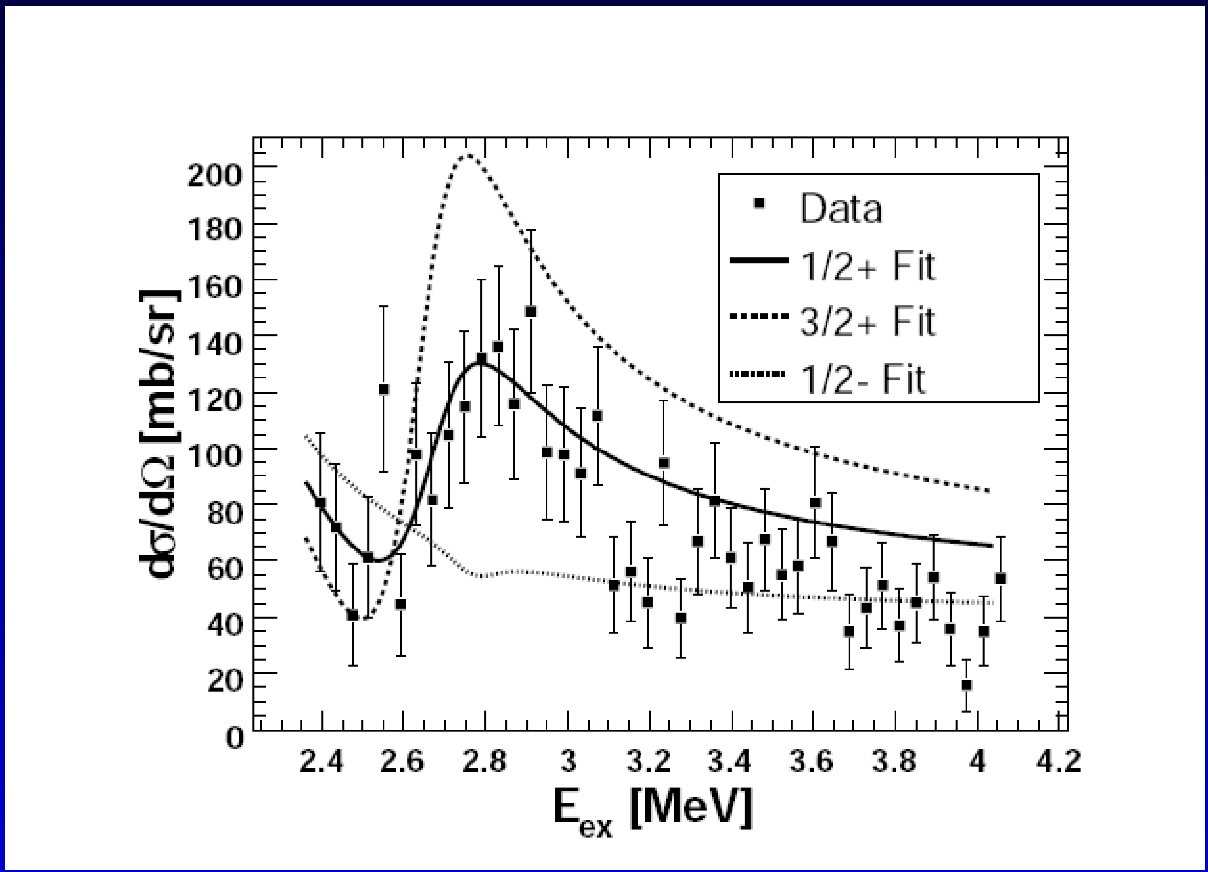
A = 13

A=13 T=3/2 isobaric chain



Structure of ^{13}O.

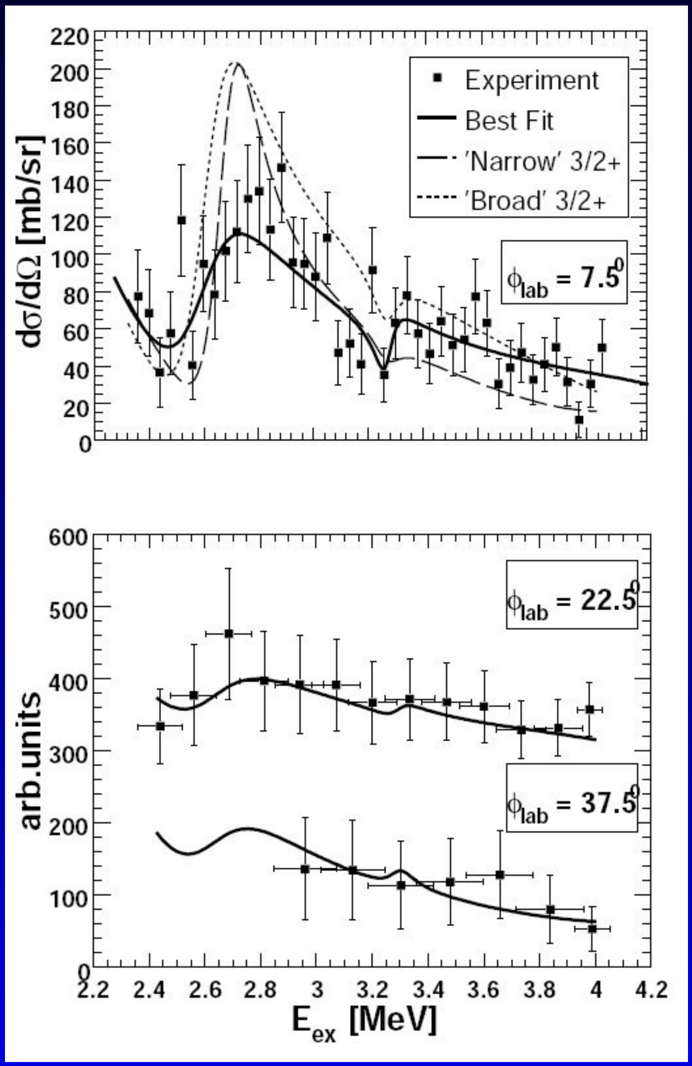
^{12}N+p -> ^{12}N+p



^{12}N + p elastic scattering excitation function (164° c.m.)

- Before this work the ^{12}N+p spectra was measured by Teranishi-san [Nucl. Phys. A718, (2003) 207] at one angle but no spin-parity assignments were given.
- Spectra can be described by a single L=0 1/2$^+$ resonance at 2.69 MeV of ^{13}O excitation energy.
- However...

Structure of ^{13}O.



- The spin-parity assignment of the first excited state in ^{13}O was performed. It is $1/2^+$ state. It is the first firm spin-parity assignment of any excited state in the T=3/2 A=13 isobaric chain!
- Some indication on the presence of the second excited state ($1/2^-$,$3/2^-$) was observed.
- Strong $3/2^+$, predicted in shell model is not observed. Either it is not there or it is canceled by the second strong 3/2+ due to destructive interference.

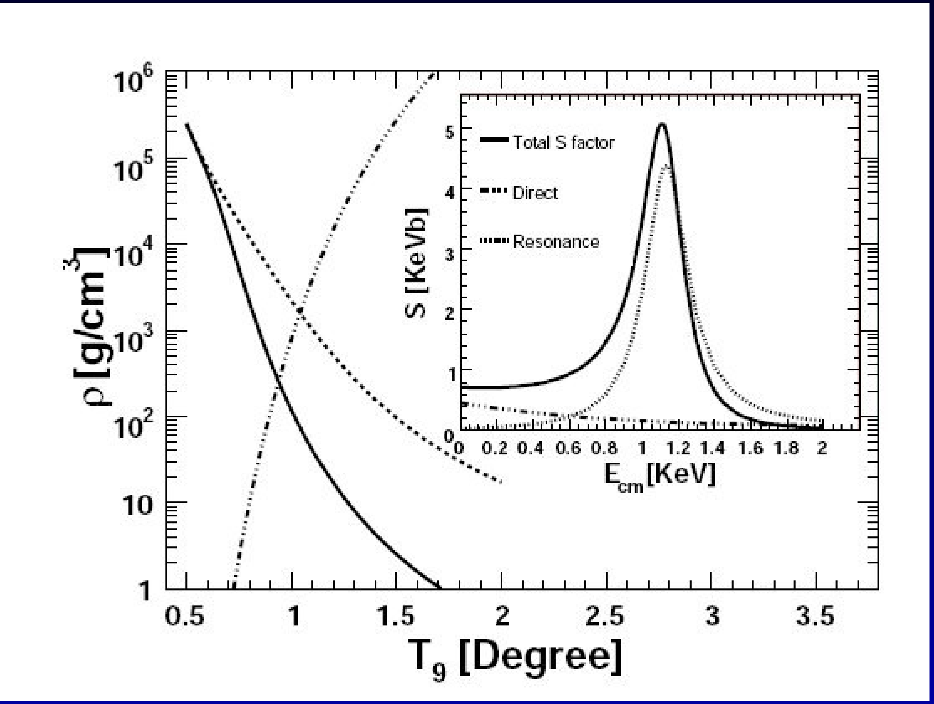
TABLE II: Resonance parameters for levels in ^{13}O

N	J^π	E_{ex} MeV	Γ MeV
1	$1/2^+$	2.69±0.05	0.45±0.1
2	$(1/2,3/2)^-$	3.29±0.05	0.075±0.03
3	$(3/2^-)^a$	(4.55)	(0.24)
4	$(3/2^+)^a$	(5.00)	(0.78)
5	$(3/2^+)^a$	(5.70)	(2.00)

[a] Distant resonances used in the R-matrix fit.

B.B. Skorodumov, et al., PRC 75 (2007) 024607

Astrophysical implications

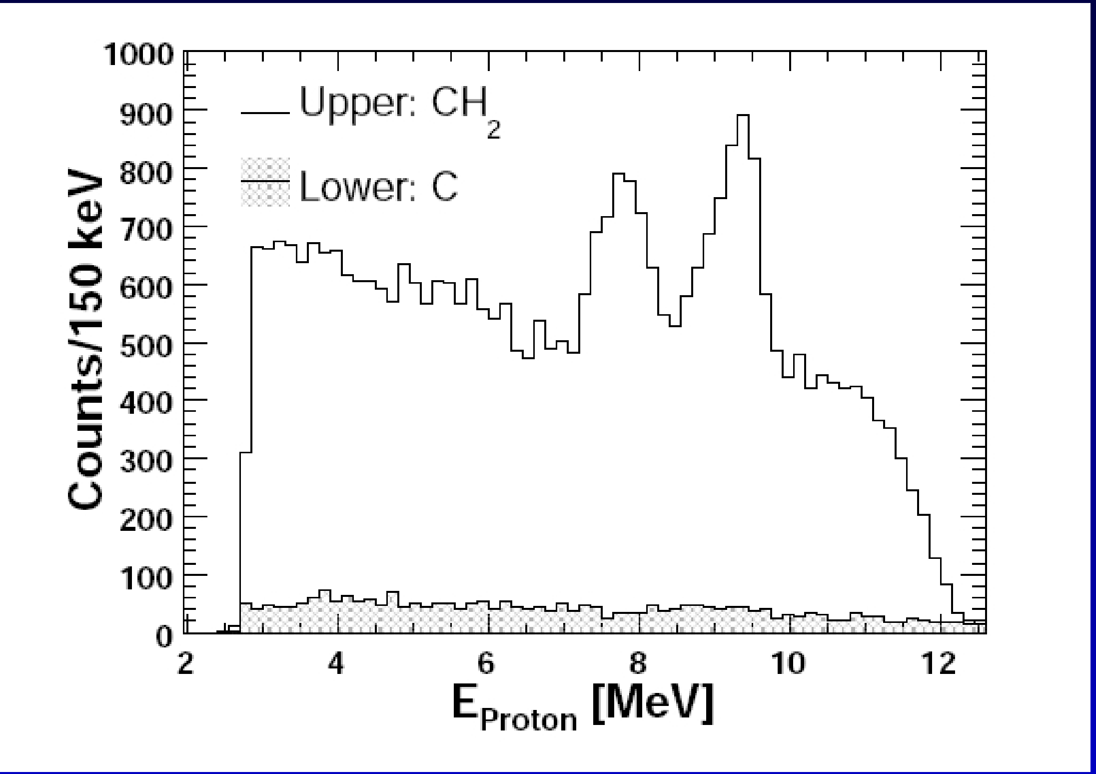


Solid line represents conditions at which proton capture rate equals to the rate of positron emission. Dashed curve – previous result, which was based on systematics.

- Reaction chain $^3He(\alpha,\gamma)^7Be(\alpha,\gamma)^{11}C$ could represent an important path from helium to carbon isotopes in very low metallicity massive stars, bypassing the 3α process.
- ^{11}C returns back to heliums if decays by β^+. $^{11}C(\beta^+)^{11}B(p,\alpha)^8Be(^4He,^4He)$
- However, it can capture p, and produce ^{12}N.
- Three paths are available from there, photo-disintegration, positron emission and proton capture. $^{12}N(p,\gamma)$ reaction rate is needed to determine the actual path.

Isobaric analogs.
T=3/2 states in ^{13}C.

- ^{12}B+p->^{13}C(T=3/2)->p+^{12}B
- Two narrow states observed at 19.8 and 20.3 MeV excitation energy in ^{13}C.
- This is 15 MeV ABOVE the neutron decay threshold, yet they are only few hundred keV wide and strongly populated in ^{12}B(p,p) reaction! => T=3/2 state!



Excitation function of
^{12}B + p elastic scattering

T=3/2 states in ^{13}C.

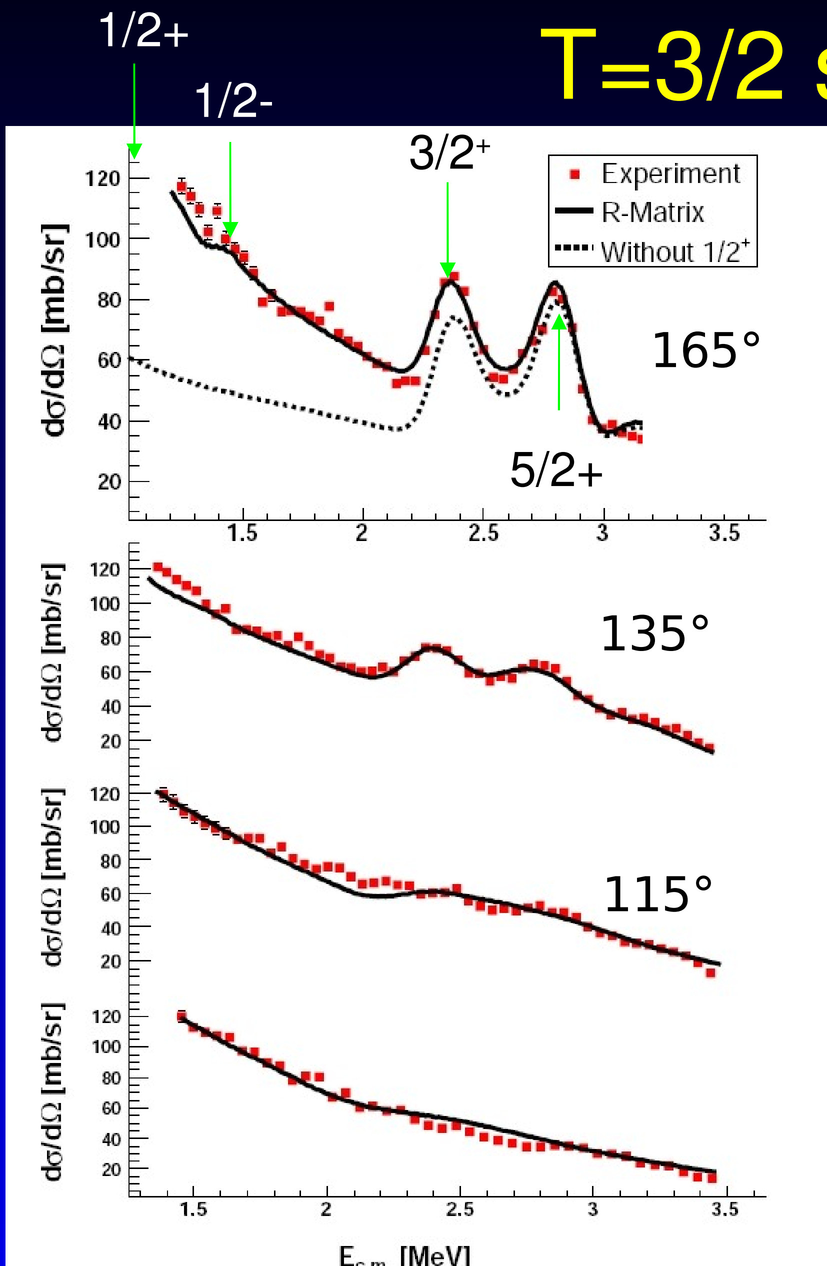
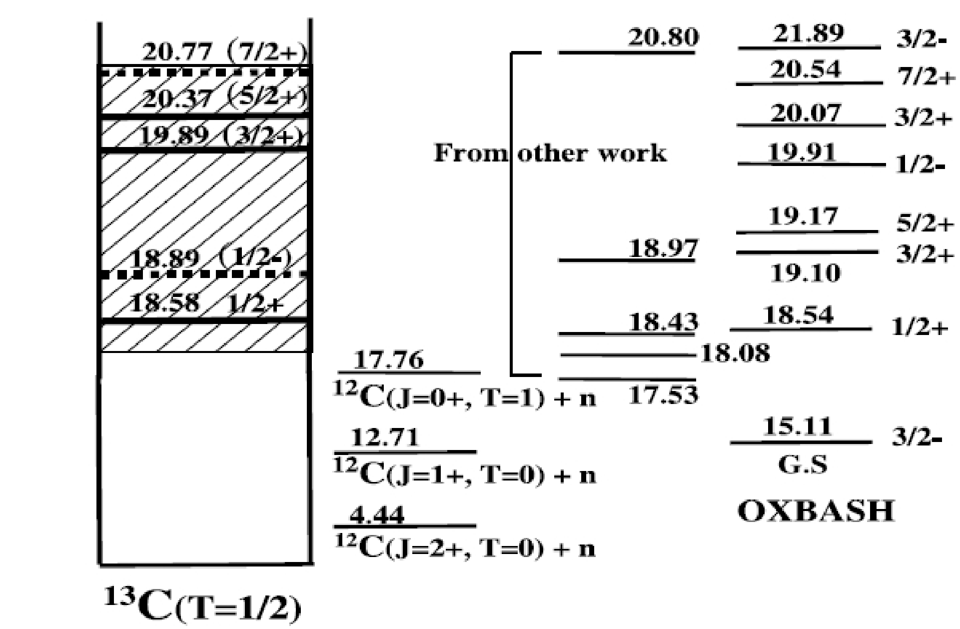


Table I: Resonance parameters for levels in ^{13}C.

L	J^π	$E_{c.m.}$ MeV	E_{ex} MeV	Γ_{exp} keV	$S_{s.p.}$	S_{OXBASH}
0	$1/2^+$	1.05	18.58	411	0.89	0.67
(1)	$(1/2^-)$	1.36	18.89	10	0.07	0.06
	$(3/2^+)$	2.36	19.89	109	-	-
0				71	0.04	0.27
2				40	0.51	0.30
2	$(5/2^+)$	2.84	20.37	98	0.48	0.21
(2)	$(7/2^+)$	3.24	20.77	457	0.99	0.29

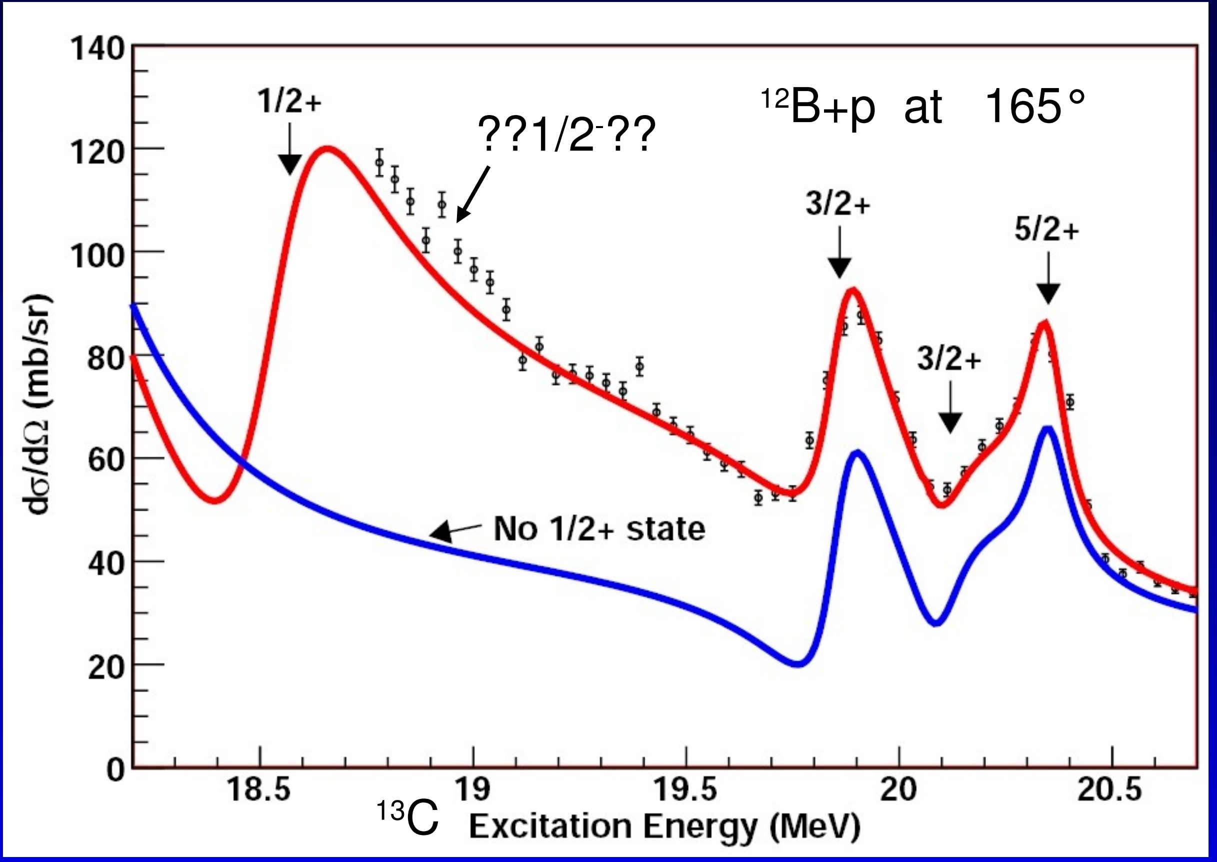


T=3/2 states in ^{13}C.

- Not over yet!
- Spectra of ^{13}B, measured in $^{11}B(t,p)$ [R. Middleton, NPA 51 (1964)] reaction has 5 peaks in the energy range from 3.5 to 4.5 MeV. Only 3(4) T=3/2 states in ^{13}C are accounted for in this narrow interval.
- Shell model calculations predict much stronger L=0 contribution to the $3/2^+$ state. The L=0 strength is missing (as in ^{13}O case).
- Another solution seems to be possible (and likely):

T=3/2 states in ^{13}C.

J^{π}	E_{ex}(MeV)	Γ(keV)
$1/2^{+}$	18.55	350
$(1/2^{-})$	(18.9)	(~10)
$3/2^{+}$	19.83	190
$3/2^{+}$	20.09	190
$5/2^{+}$	20.32	120



T=3/2 states in ^{13}C.

- Two narrow structures were observed in ^{12}B+p excitation function.
- R-matrix analysis combined with information available for the other members of the A=13 T=3/2 isobaric chain infer that the observed spectra can be explained by four positive parity T=3/2 states with spin parities $1/2^+$, $3/2^+$, $3/2^+$ and $5/2^+$.
- NO T=1/2 states are necessary to obtain a good fit to the data!

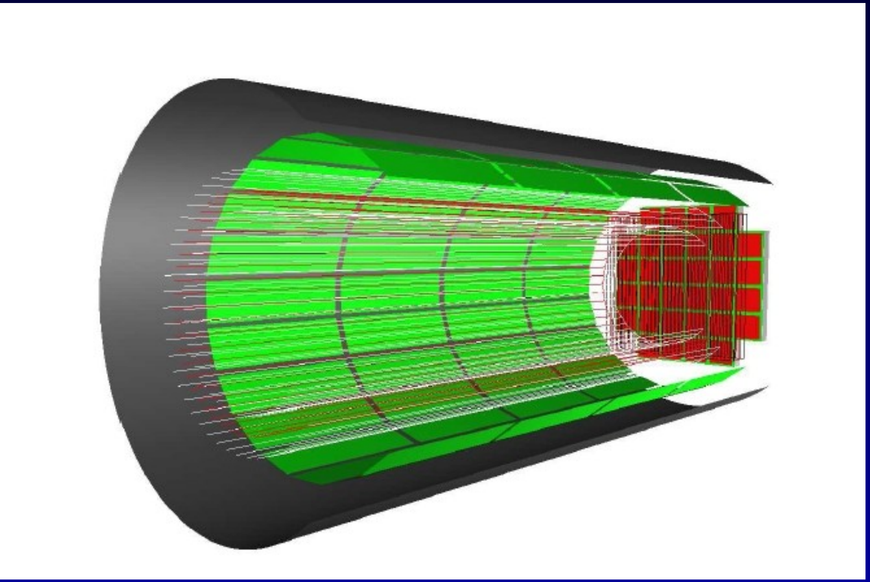
While significant progress was achieved in spectroscopy of the low lying T=3/2 states in A=13 isotopes it is clear that further studies are necessary to verify the spin-parity assignments suggested above.

In order to study resonances with radioactive beams we need to use thick target:

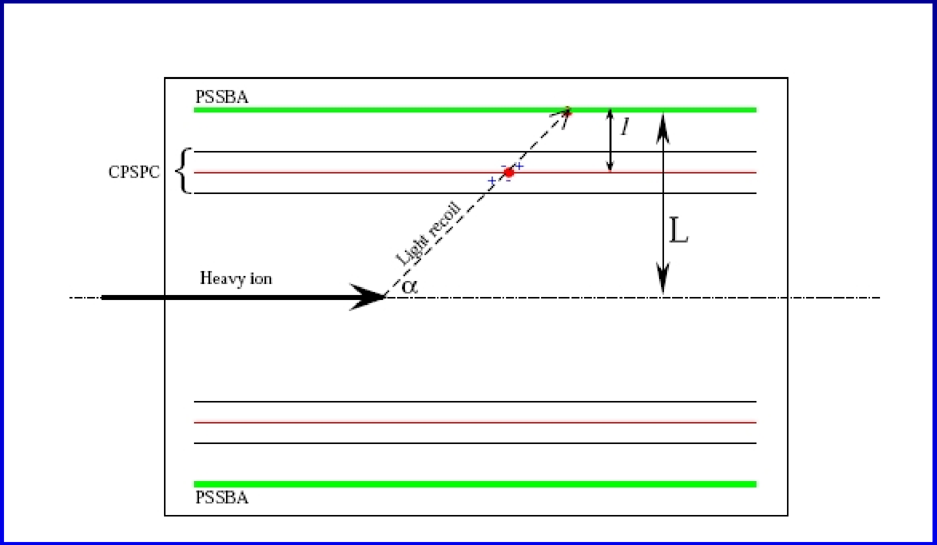
- Active target -> limited beam intensity.
- Inverse geometry and thick target technique -> degradation of resolution with angle, “inelastic” problem.

Solution -> hybrid technique

Florida Detector for Resonance Reaction Studies (FLORES).



- FLORES is a gas chamber.
- Gas serves as a target (helium or hydrogen) and as active volume.
- Areas of high ionization are avoided by special arrangement of gas counters electrodes.



- High granularity arrays of silicon position-sensitive detectors and CsI(Tl) scintillators will be used to measure energy/energy loss/position of light recoils and low energy gamma rays.
- FLORES optimized to measure:
  (p,p); (p,p'); (α,α); (α,α'); (α,p); (p,α)
  reactions with radioactive beams.

SUMMARY

- Spectroscopy of light exotic nuclei brings new information on the details of nuclear interaction, provides an important link between structure and reaction theories and also plays significant role in nuclear astrophysics.
- Resonance reactions give direct access to the unbound states in the exotic systems but require the use of radioactive beams.
- While limited success has been achieved in resonance reaction studies with radioactive beams using the thick target technique a lot more development is needed to bring as to the next stage of exotic nuclei exploration.

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