Resonance scattering with exotic beams - past, present, and future

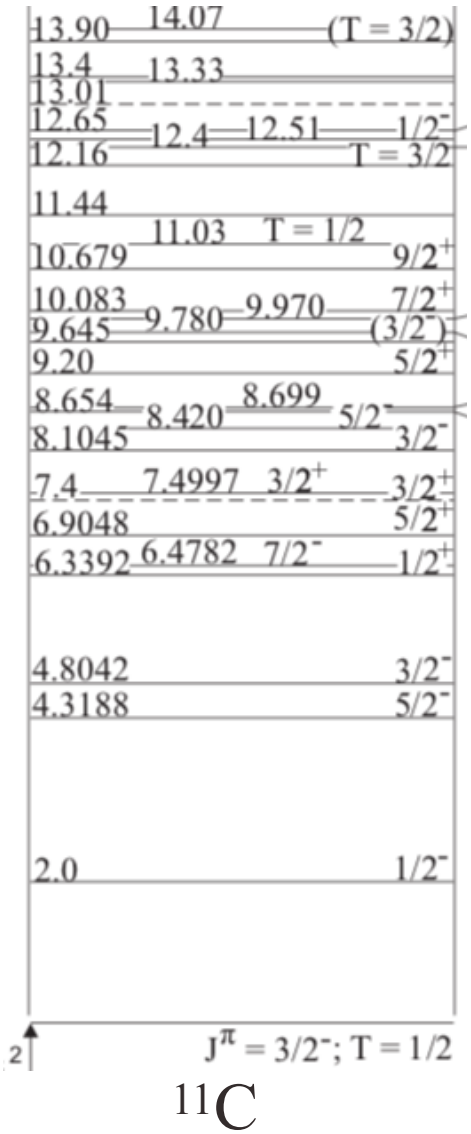
G.V. Rogachev

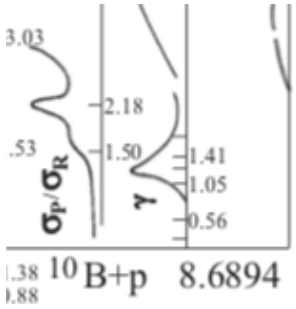
TEXAS A&M UNIVERSITY

Outline

- [x] Historical perspective
- [x] Experimental aspects
- [x] Proton rich nuclei
- [x] Clustering phenomena
- [x] Neutron rich nuclei

Early days of RS…

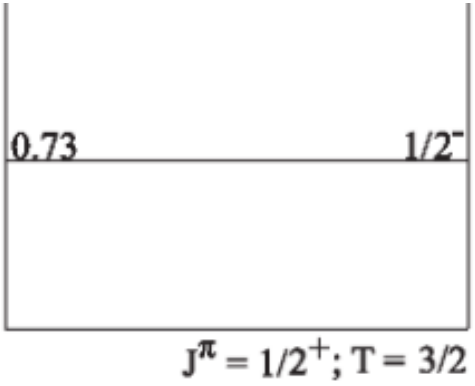




- ☑ Well understood theoretically
- ☑ Perfect energy resolution (~10 keV)
- ☑ Limited accessible energy range

- ☑ Special cases:
  - ✦ IAS (ex. J. Fox, D. Robson in 60s at FSU)
  - ✦ alpha clusters (ex. H.T. Richards, et al., U of Wis. - Mad).

Recent history…



Exotic nuclei

- ☑ Low lying states are accessible
- ☑ Level density is low

$\frac{-1.4893}{^{10}C+p}$

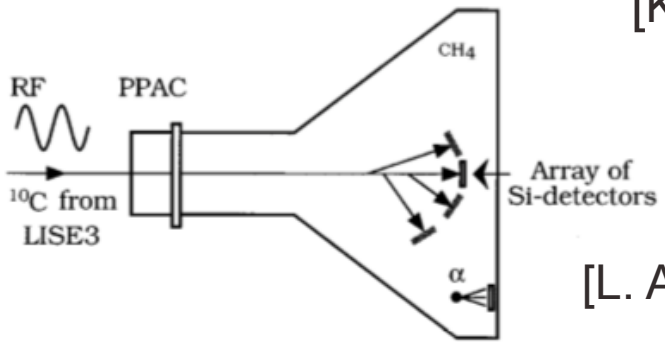
- ☑ Need R/A beams and
- ☑ New Experimental approach

Experimental evolution

FROM:

Thick Target Inverse Kinematics technique

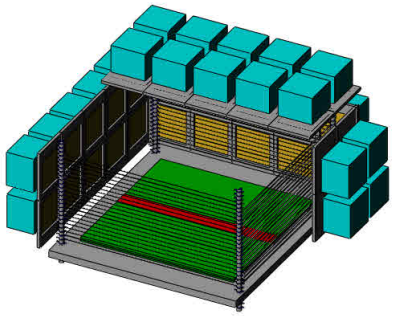
[K.P. Artemov, et al., Sov. J. Nucl. Phys. (1990)]



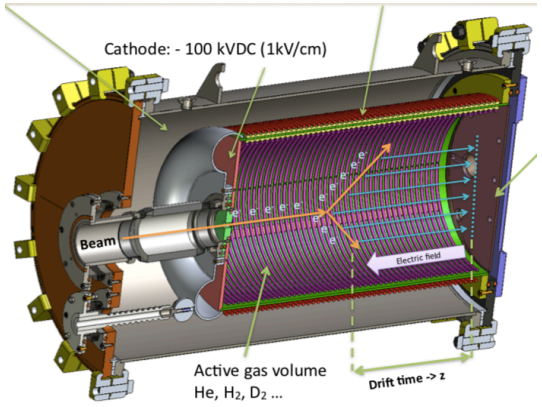
[L. Axelsson, et al., Phys. Rev. C, RC (1996)]

TO: Active Targets

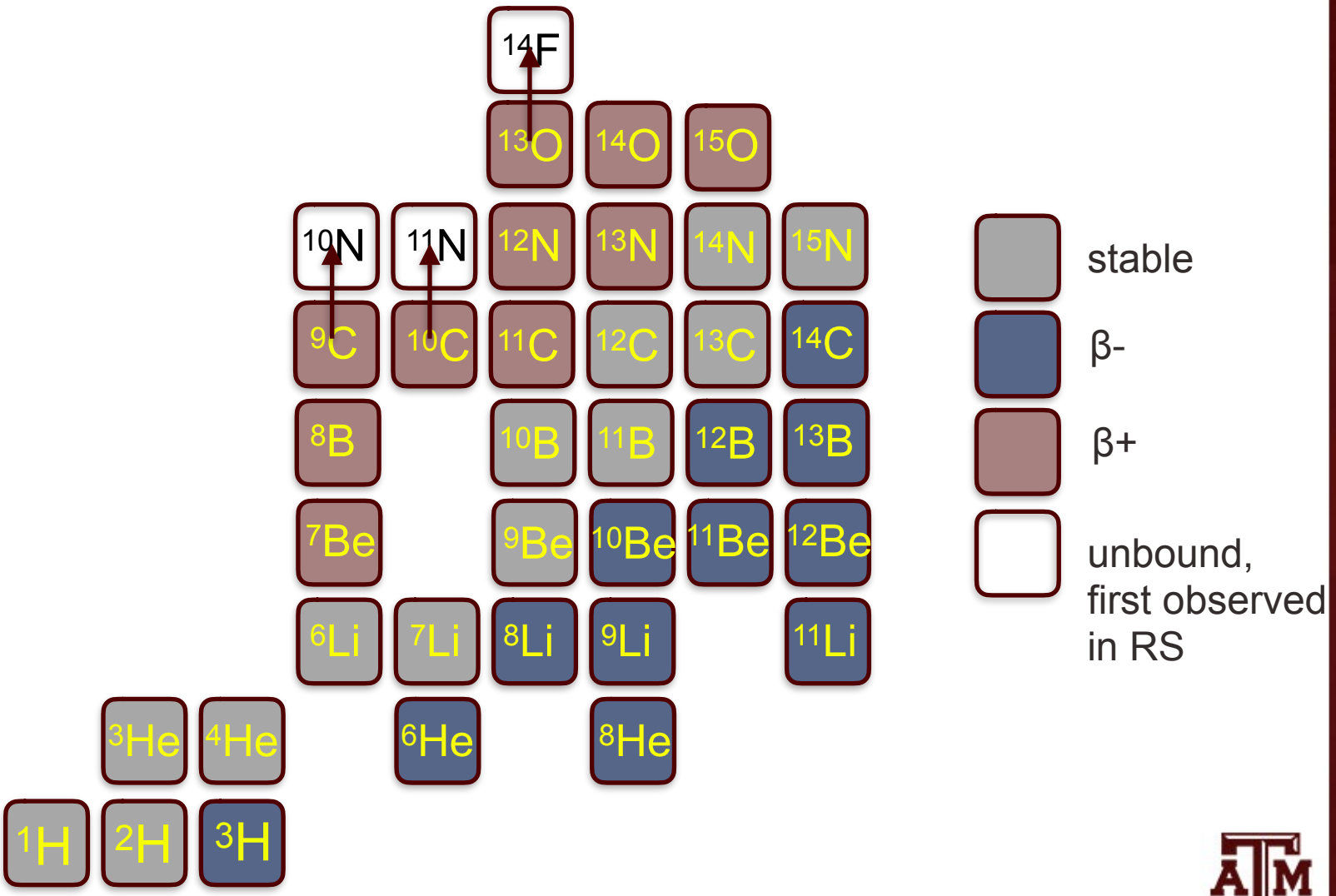
TexAT



AT-TPC

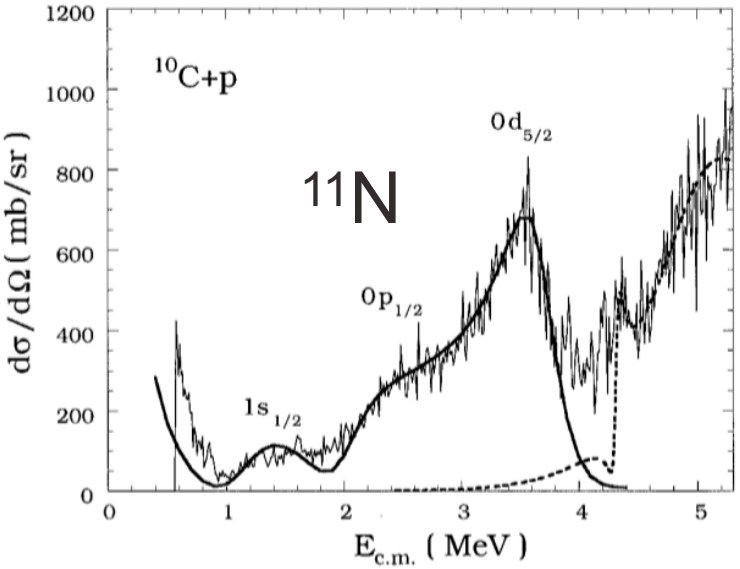


Proton rich nuclei

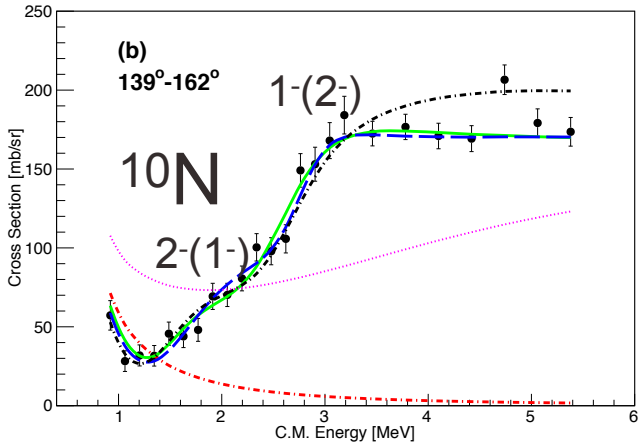


Proton rich nuclei

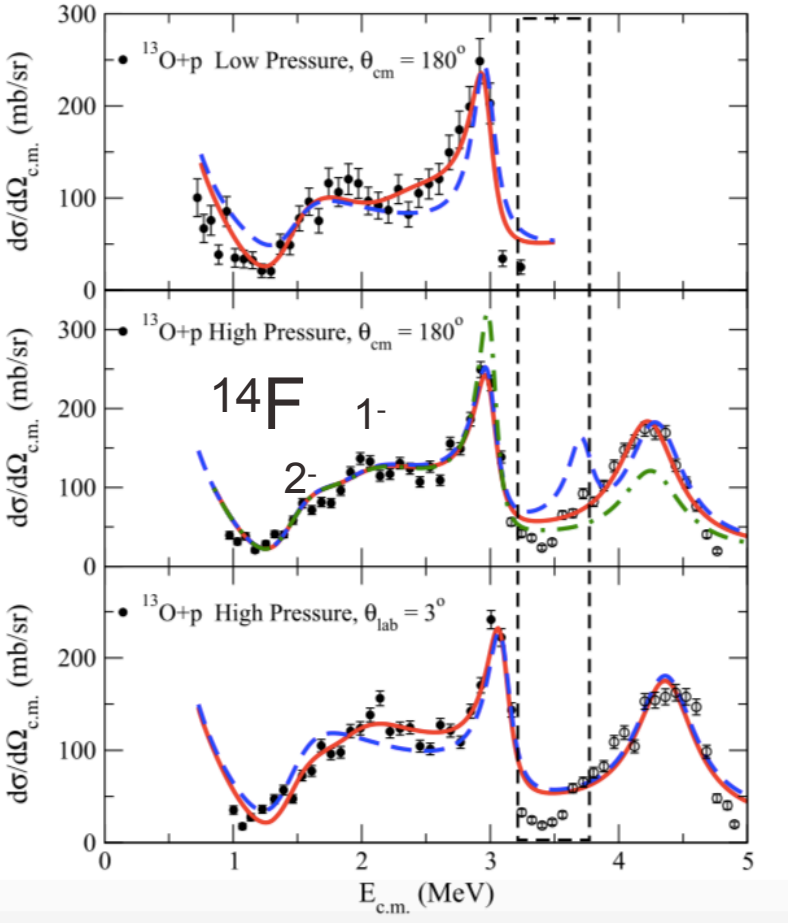
[L. Axelsson, et al., Phys. Rev. C, RC (1996)]



[J. Hooker, et al., Phys. Lett. B, (2017)]

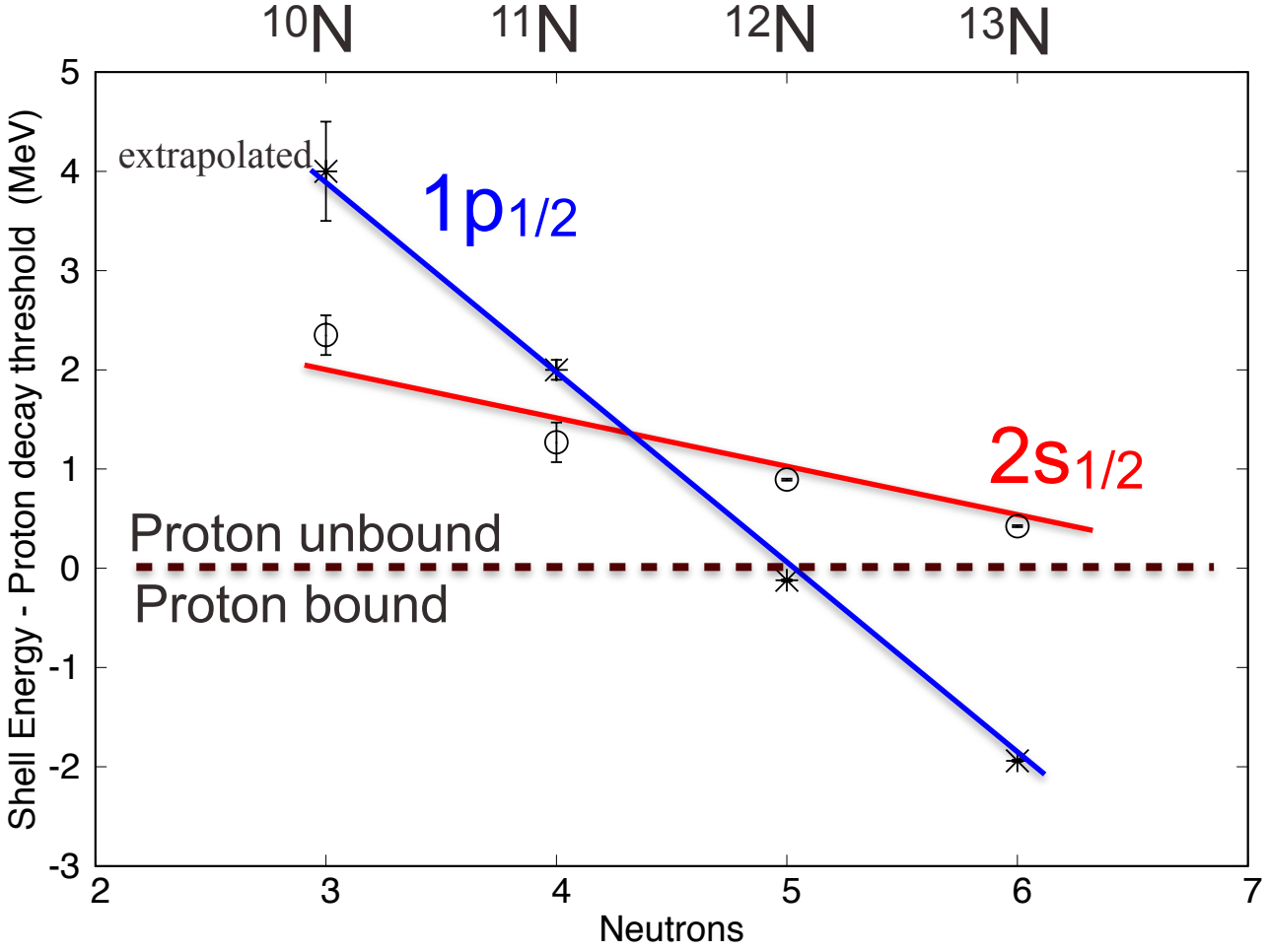


[V.Z. Goldberg, et al., Phys. Lett. B (2010)]



Talk of J. Hooker on structure of ^{9}C in this session

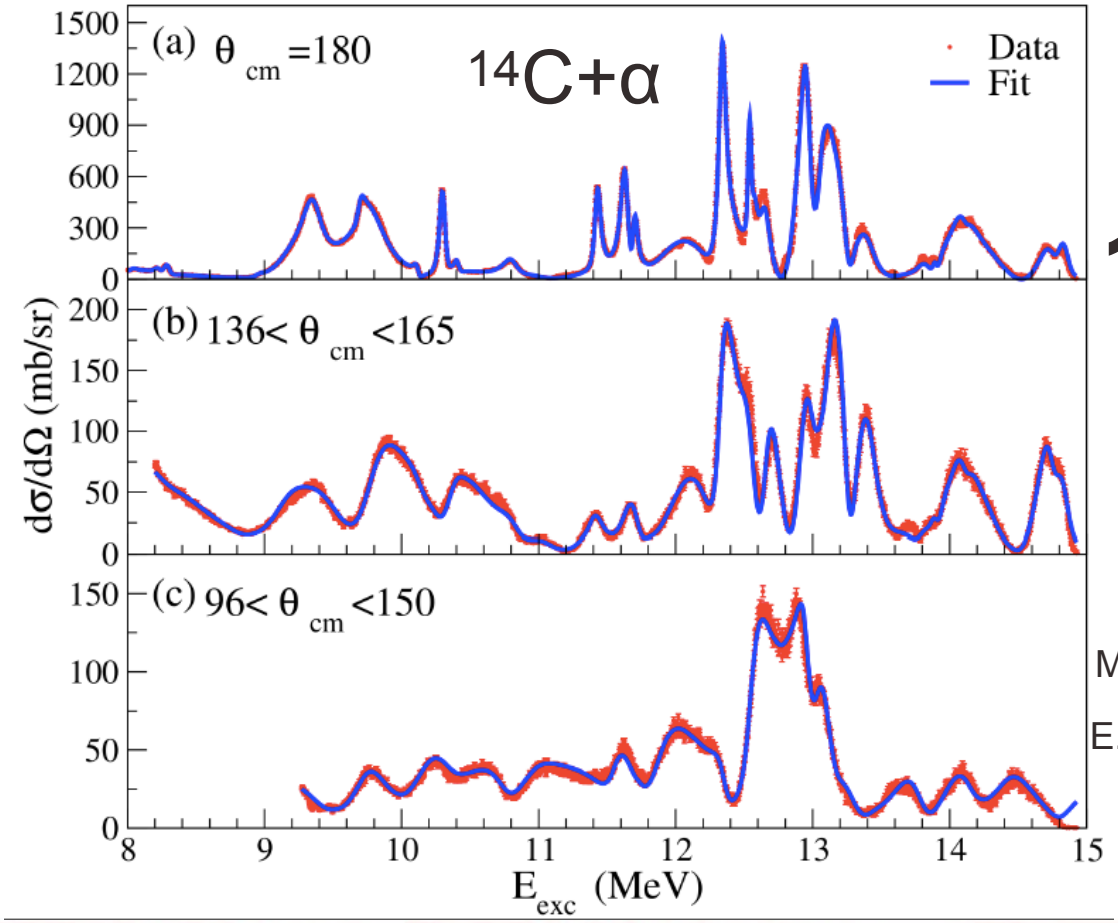
Evolution of 1p1/2 and 2s1/2 shells for neutron deficient Z=7 isotopes

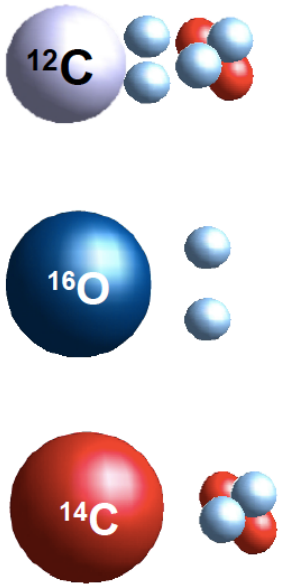


Also discussed by E. Vigezzi on Tuesday for N=7 isotones

Clustering phenomena

- ☑ Clustering plays important role in nuclear structure
- ☑ Alpha clusters manifest strongly in resonance scattering



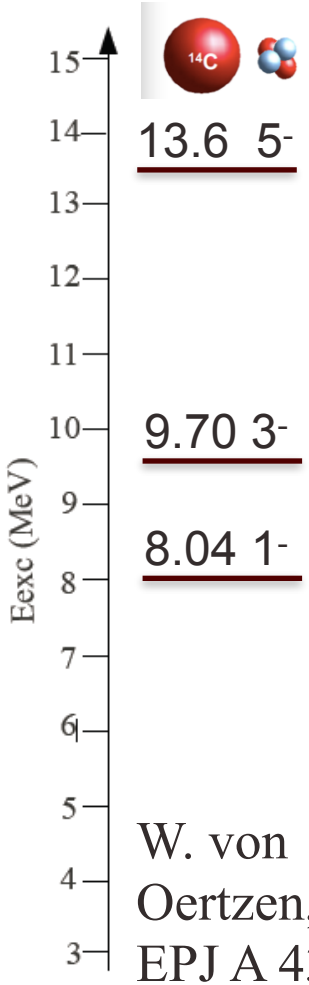


18O

M. Avila, et al., PRC (2014)

E. Johnson, et al., EPJA (2009)

Negative parity α cluster band in ^{18}O



13.6 5$^-$

9.70 3$^-$

8.04 1$^-$

W. von Oertzen, et al. EPJ A 43 (2010)

13.82 5$^-$ $\theta^2 < 0.01$

9.70 3$^-$ $\theta^2 = 0.04$

8.04 1$^-$ $\theta^2 = 0.02$

R-matrix fit to the $^{14}C+\alpha$ experimental data

1$^-$

10.8 1$^-$ $\theta^2 = 0.29$

9.76 1$^-$ $\theta^2 = 0.46$

9.19 1$^-$ $\theta^2 = 0.20$

R-matrix fit to the $^{14}C+\alpha$ experimental data

3$^-$

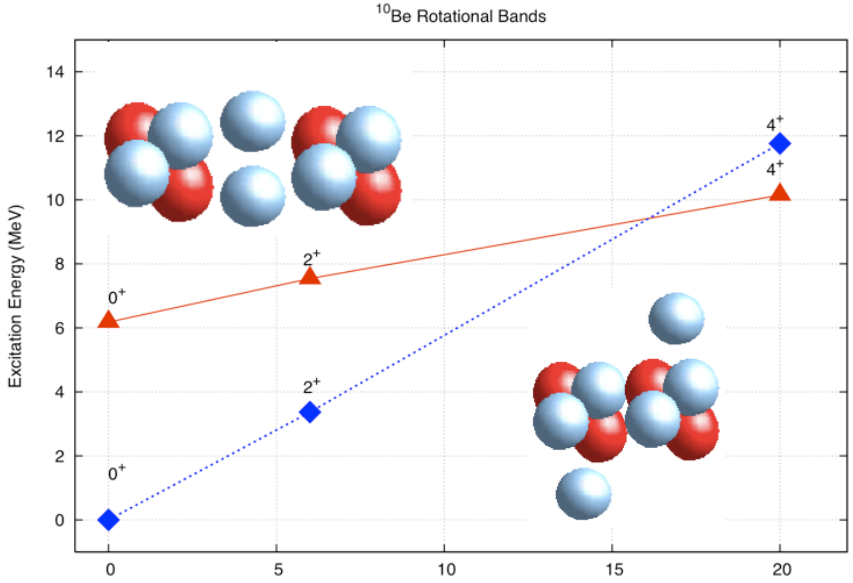
11.95 3$^-$ $\theta^2 = 0.17$

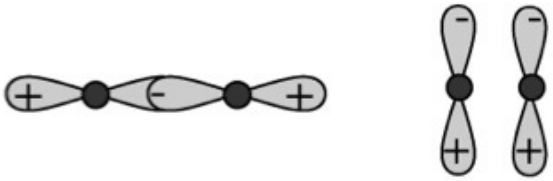
9.35 3$^-$ $\theta^2 = 0.48$

8.28 3$^-$ $\theta^2 = 0.18$

R-matrix fit to the $^{14}C+\alpha$ experimental data

Cluster structure of ^{10}Be

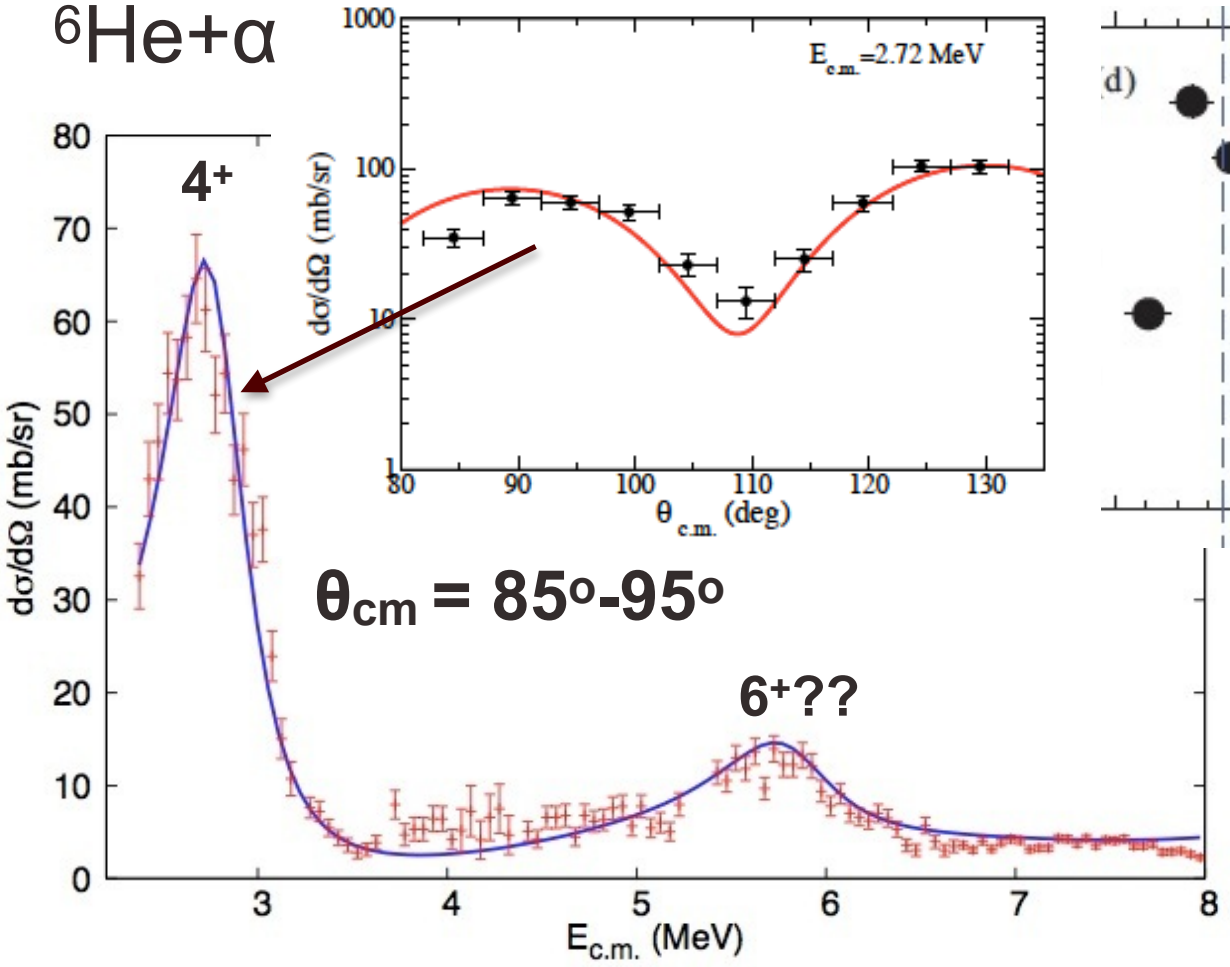




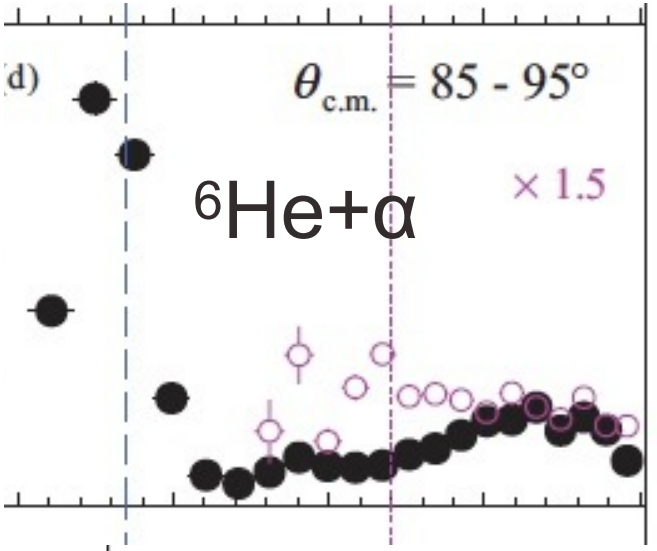
- Rotational band with high moment of inertia built on 0^+ at 6.18 MeV
- 10.15 MeV state reported to be 4^+ [1,2] and extremely clustered [1]. Other spin-parity assignment was reported 3^- [3].
- Believed to be associated with α-2n-α molecular rotational band.
- The next member of the highly deformed rotational band, 6^+, was predicted [4].

[1] M. Freer, et al., PRL 96, 042501 (2006)
[2] M. Milin, et al., NPA 753, 263 (2005)
[3] N. Curtis, et al., PRC 64, 044604 (2001
[4] Yu. Tchuvil'skiy, et al., Phys. At. Nucl. 73 (2010)

Cluster structure of ^{10}Be

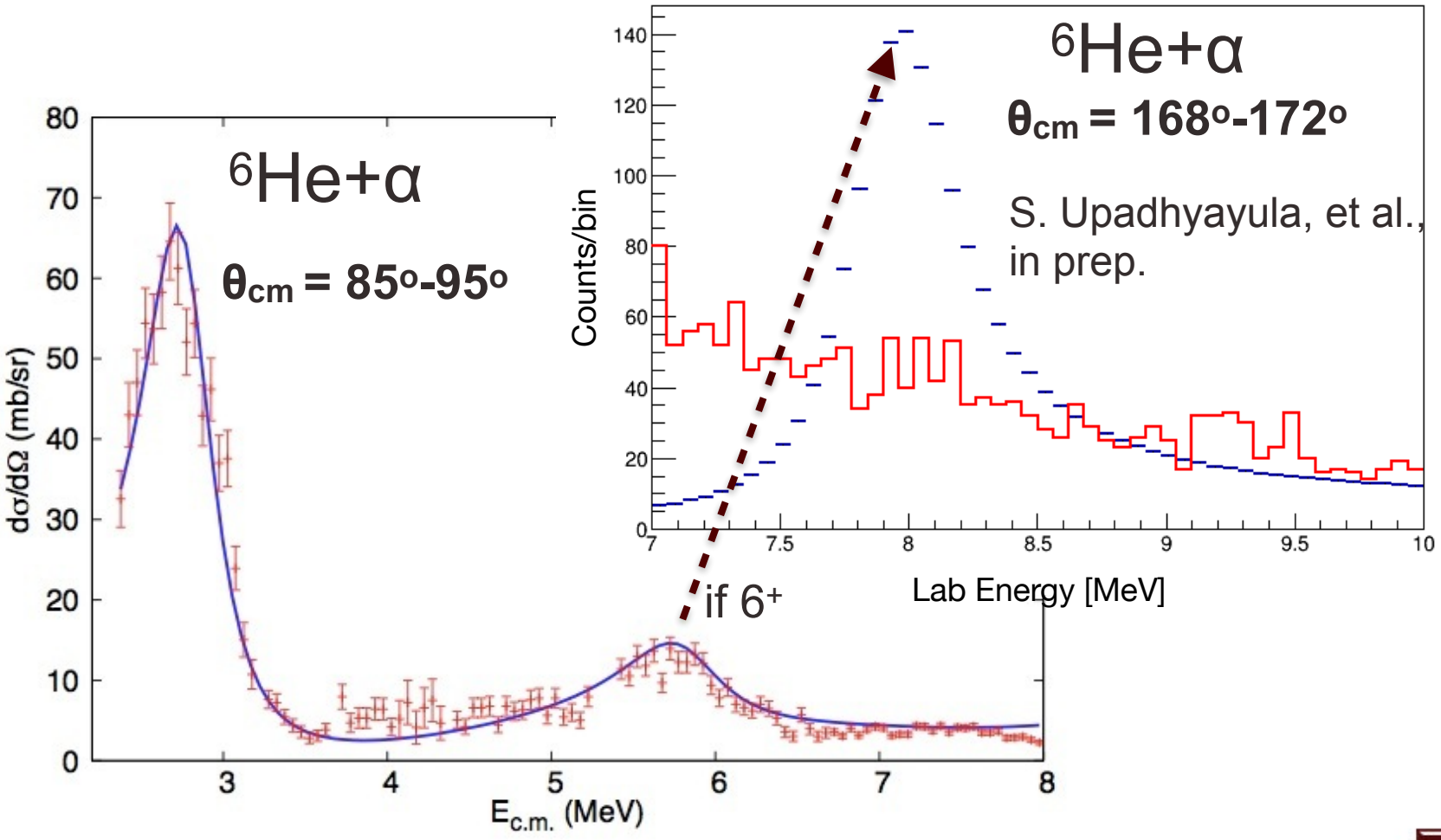


E. Koshchiy, et al., NIM A (2017)



D. Suzuki, et al.,
Phys. Rev. C **87** (2013)

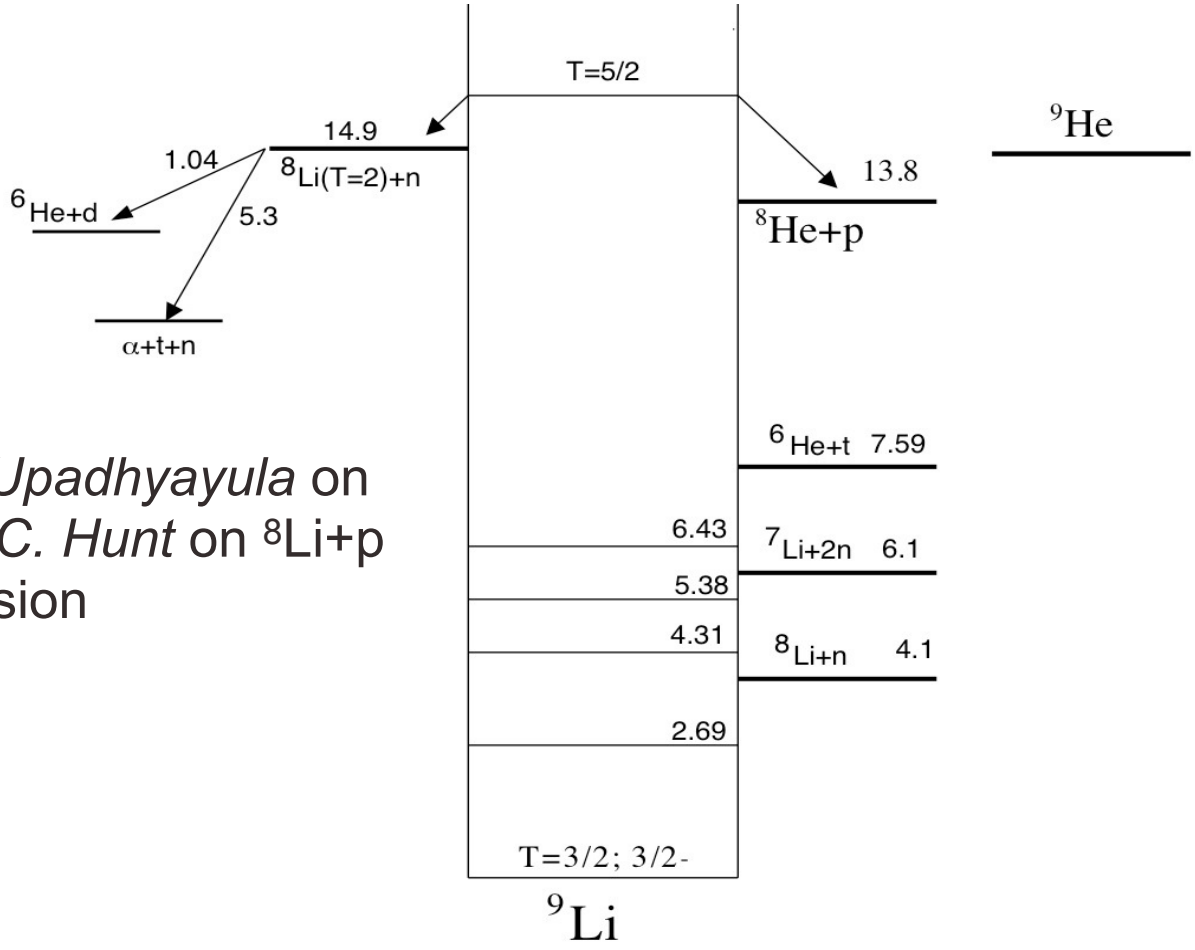
No evidence for 6^+



Also talk of D. Kim on Tuesday: ^{15}O+α and ^{15}N+α

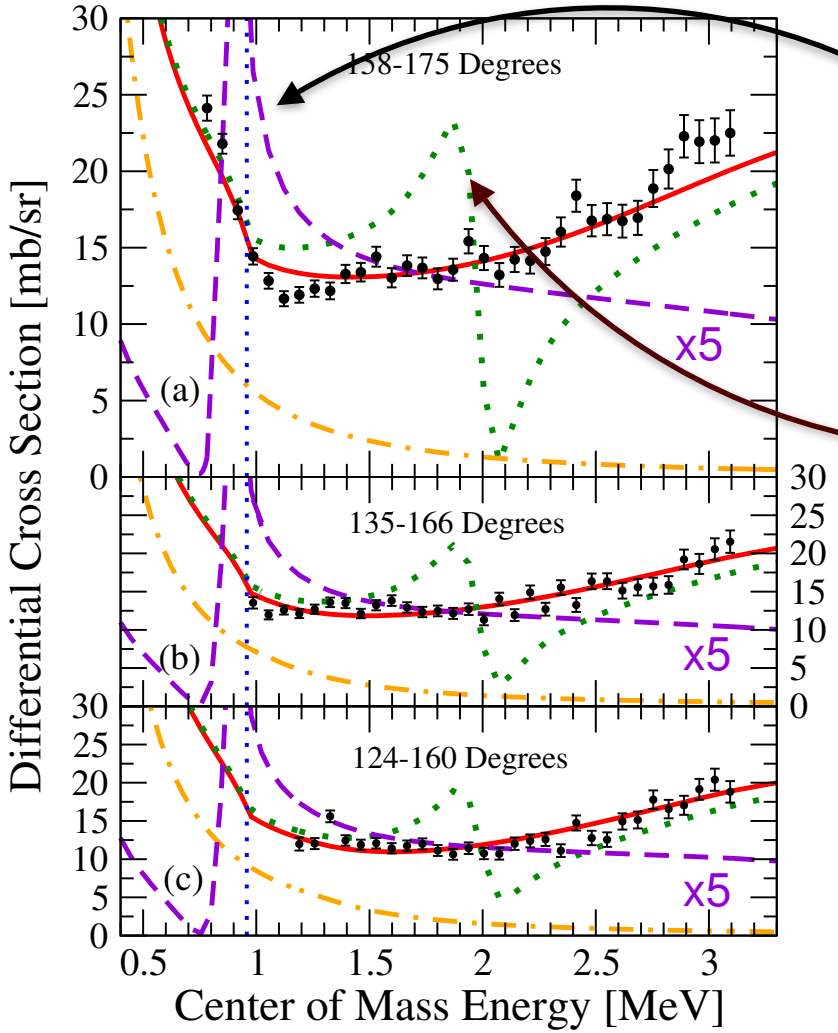
IAS in neutron rich nuclei

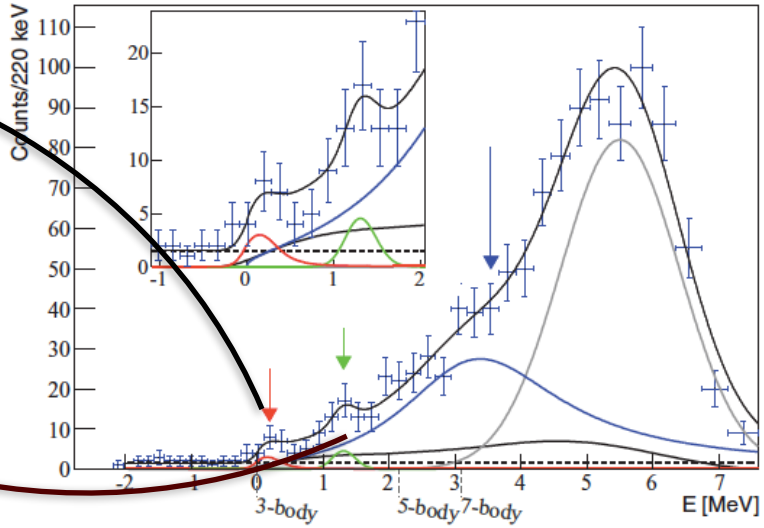
p + ^{8}He -> ^{9}Li(T=5/2) -> p + ^{8}He



ALSO:
Talks of *S. Upadhyayula* on ^{47}K+p and *C. Hunt* on ^{8}Li+p in this session

Structure of ^{9}He



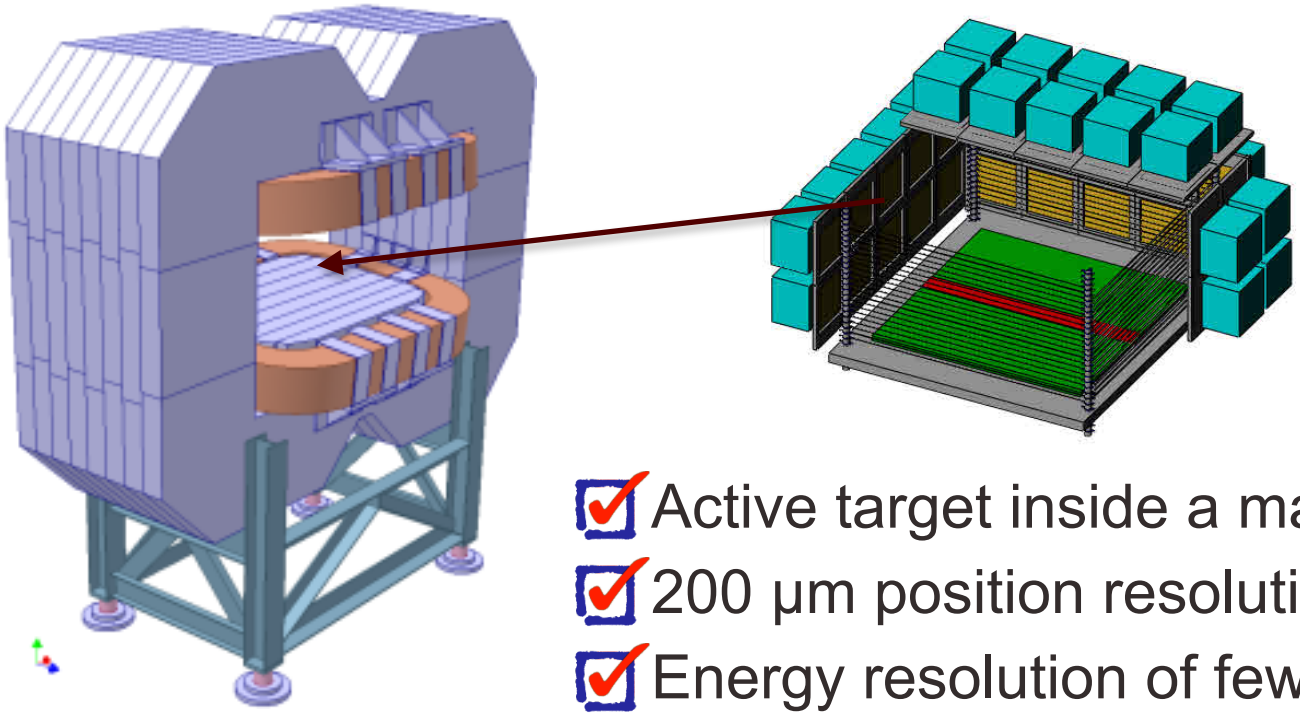


^{8}He(d,p): T. Al. Kalanee, et al., PRC 88 (2013)

E. Uberseder, et al., Phys. Lett. B, 754, 323 (2016)

- ☑ ^{8}He beam produced by ISAC facility at TRIUMF
- ☑ No narrow states were observed
- ☑ Evidence for a very broad $1/2^{+}$ state at ~2.5 MeV

Future of resonance scattering

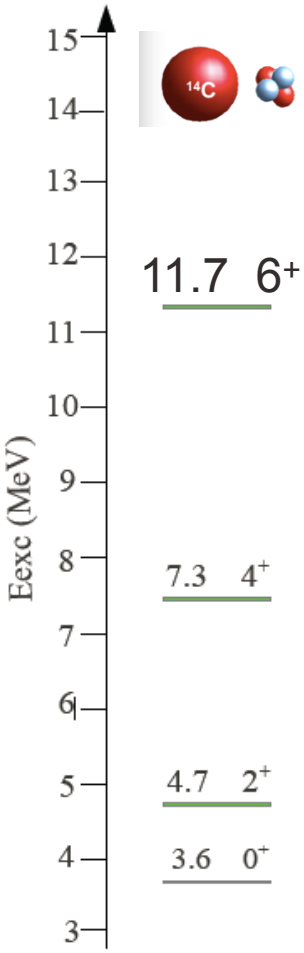


- Active target inside a magnet
- 200 μm position resolution
- Energy resolution of few keV
- Narrow resonances (IAS, astrophysics)

Conclusion

- Resonance scattering with exotic beams has many application and significant advantages
- Many results on structure of proton rich nuclei have been obtained
- Clustering phenomena studies with exotic beams is in its infancy - high statistics and wide angular range needs to be measured
- IAS states studies open a way to explore neutron rich nuclei - theoretical issues need to be resolved

Positive parity inversion doublet quasi-rotation band in ^{18}O



12.6 6^+ $\theta^2 = 0.38$

11.7 6^+ $\theta^2 = 0.23$

R-matrix fit to the $^{14}C+\alpha$ experimental data

$$\theta_\alpha^2 = \frac{\Gamma_\alpha}{\Gamma_{sp}}$$

W. von Oertzen, et al.
EPJ A 43 (2010)

13.0 6^+ $\theta^2 = 0.28$

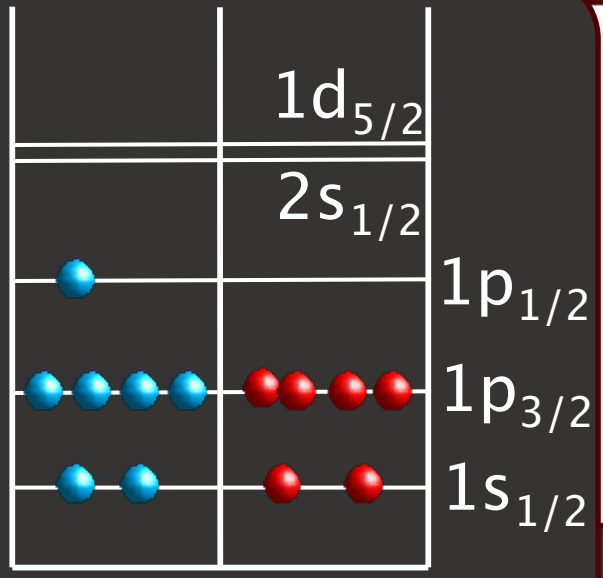
11.1 6^+ $\theta^2 = 0.20$

Cluster Nucleon Configuration Interaction Model (CNCIM)

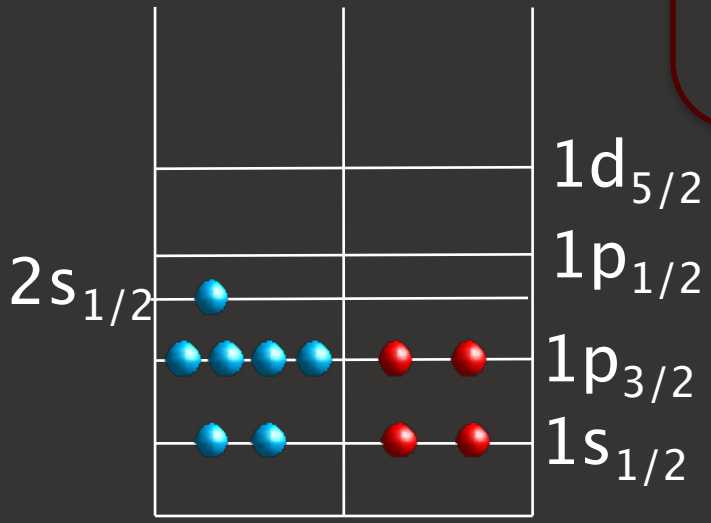
Yu. Tchuvil'sky
A. Volya

Splitting is due to strong configuration mixing $(0p)^2(1s0d)^2$ and $(1s0d)^4$

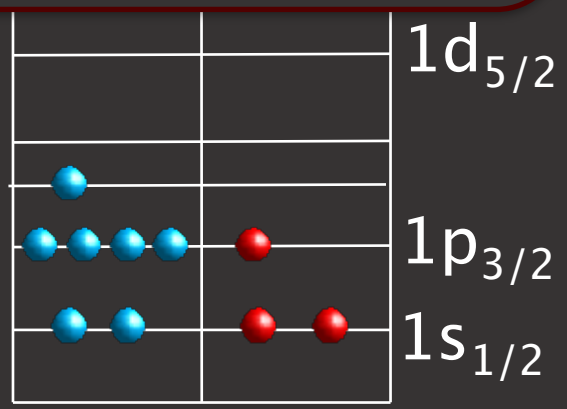
Z=7 isotopes
N=7 isotones



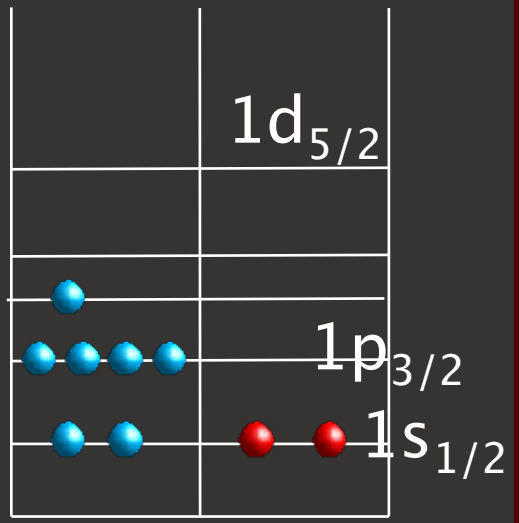
^{13}C (1/2$^-$; g.s.)
^{13}N (1/2$^-$; g.s.)



^{11}Be ½+ g.s.
^{11}N ½+ g.s.



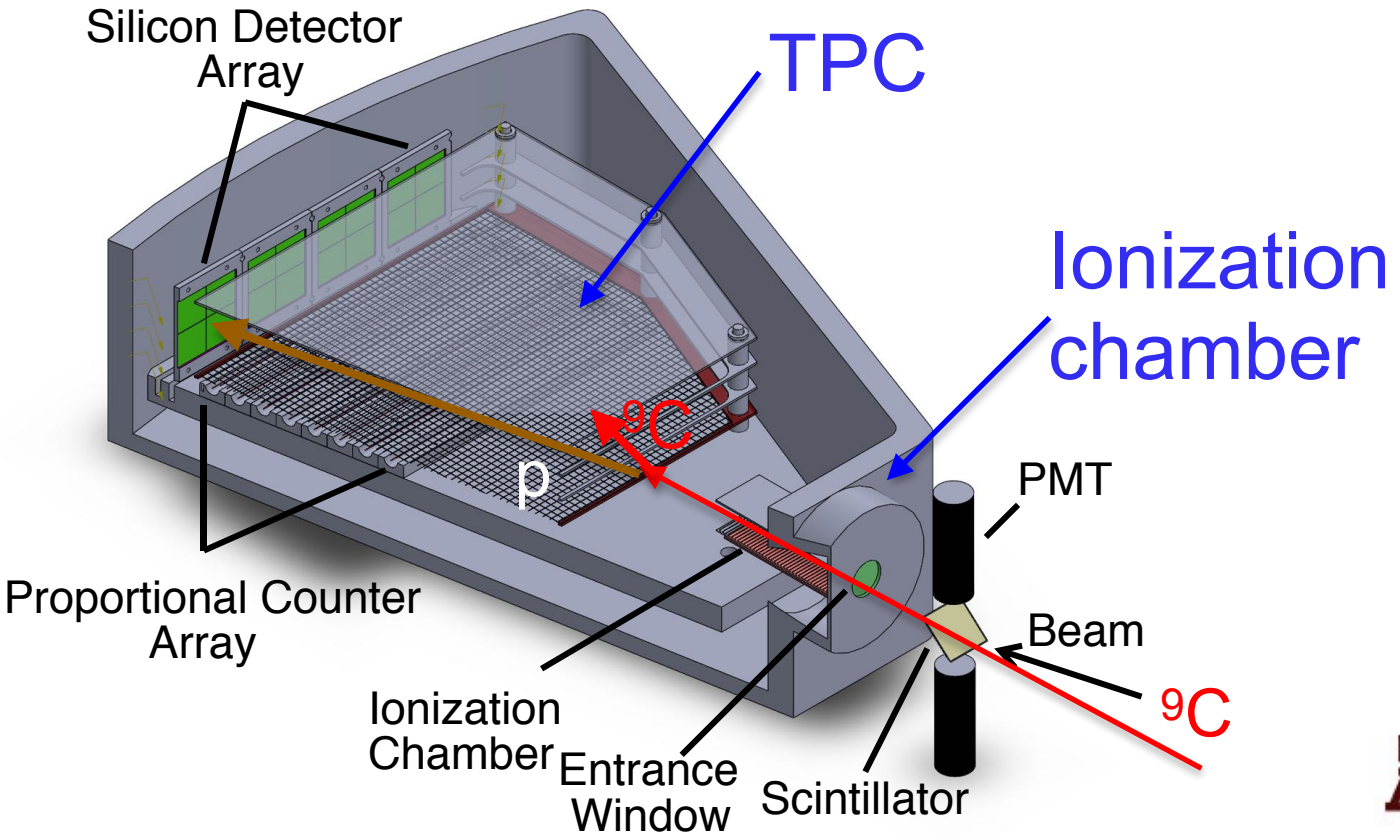
^{10}Li (2$^-$;1$^-$) L=0 g.s.?
^{10}N ?



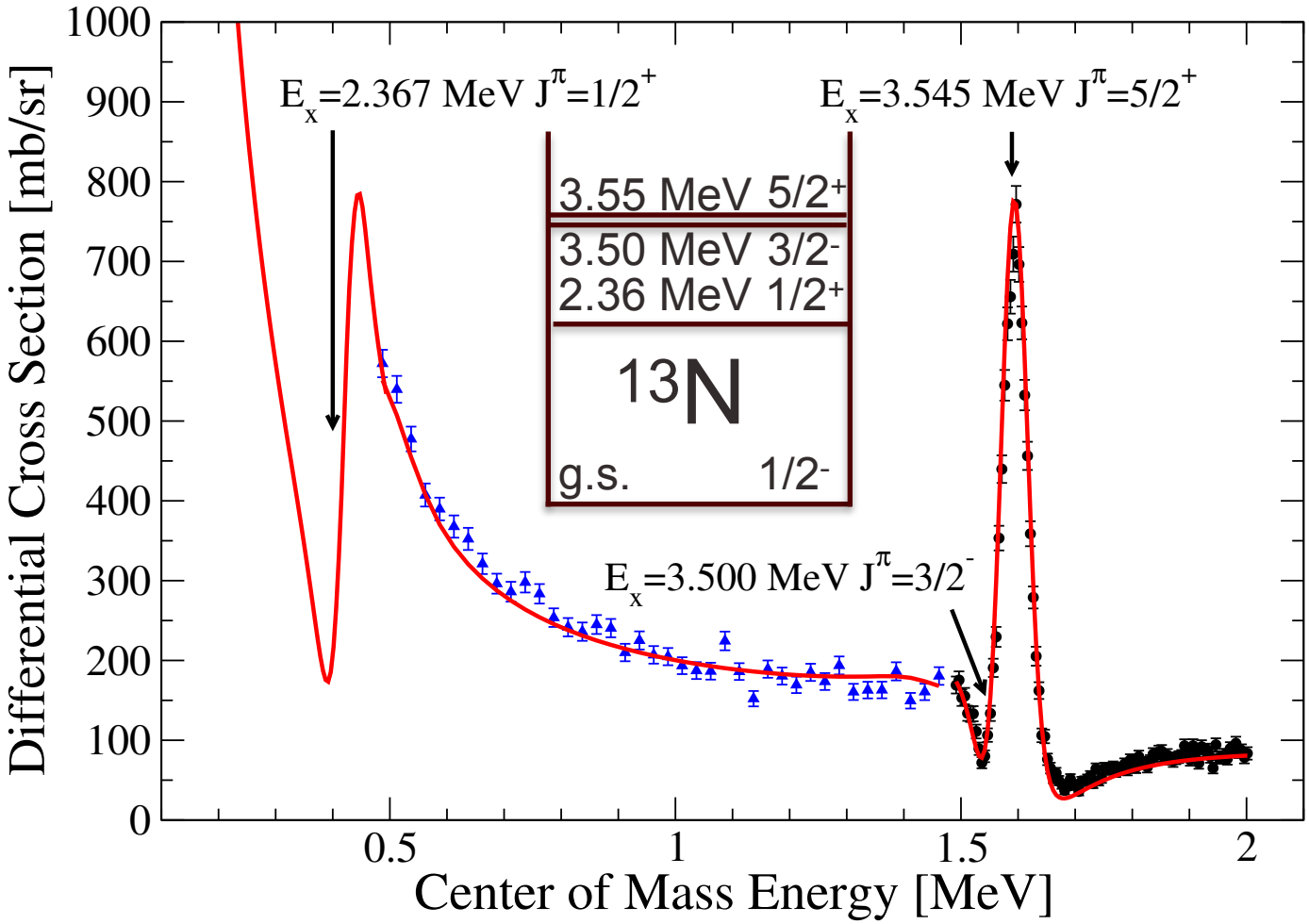
^{9}He – all over the place

Resonance scattering

- ☑ Structure of ^{10}N and ^{9}He studied using resonance elastic scattering
- ☑ Resonances in ^{10}N were directly populated in ^{9}C+p elastic scattering
- ☑ Resonances in ^{9}He were studied through T=5/2 IAS in ^{9}Li, populated in ^{8}He+p elastic scattering



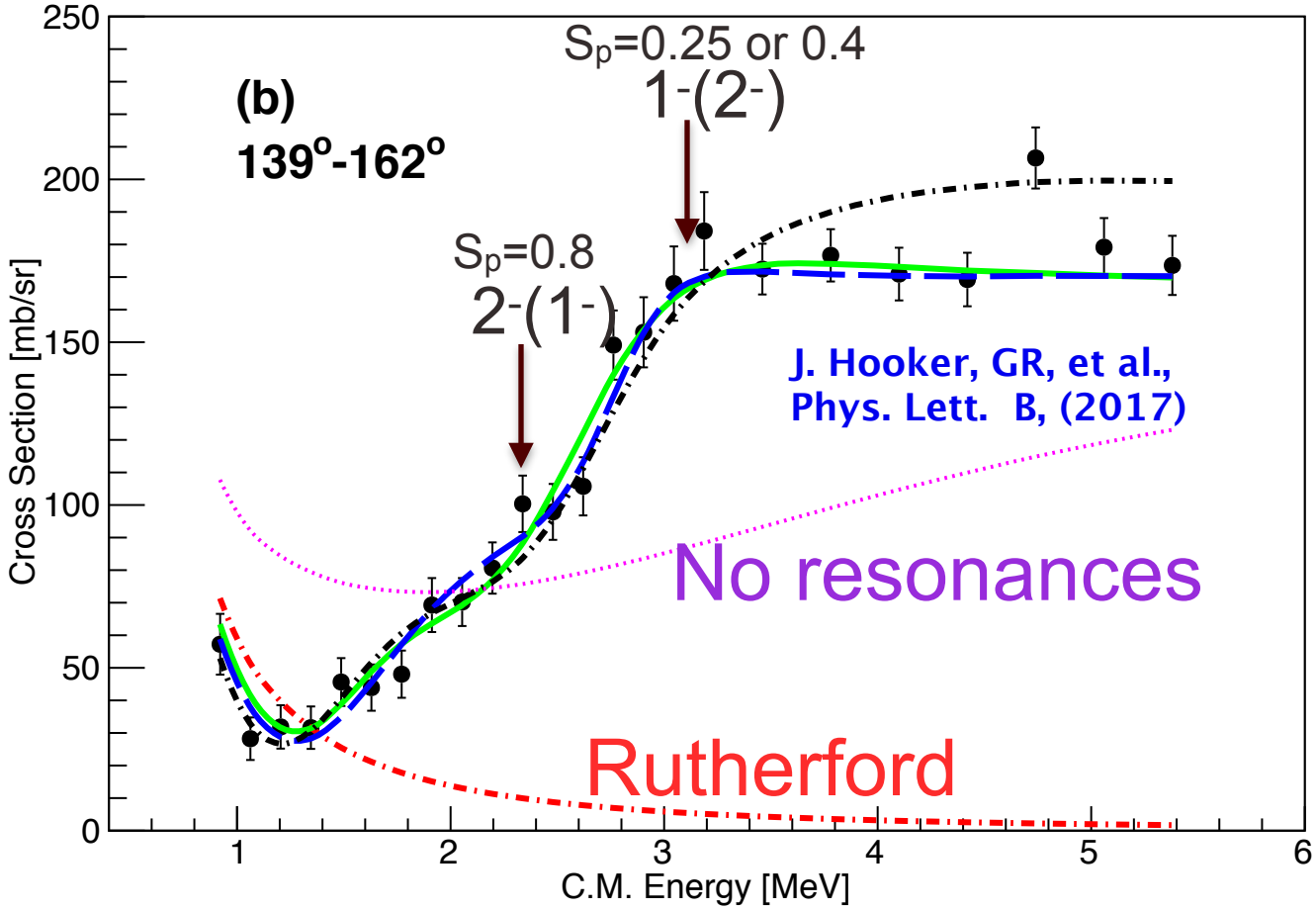
Test with ^{12}C beam - states in ^{13}N



- Red curve is an R-matrix calculation (not a fit!) based on known properties of the states in ^{13}N

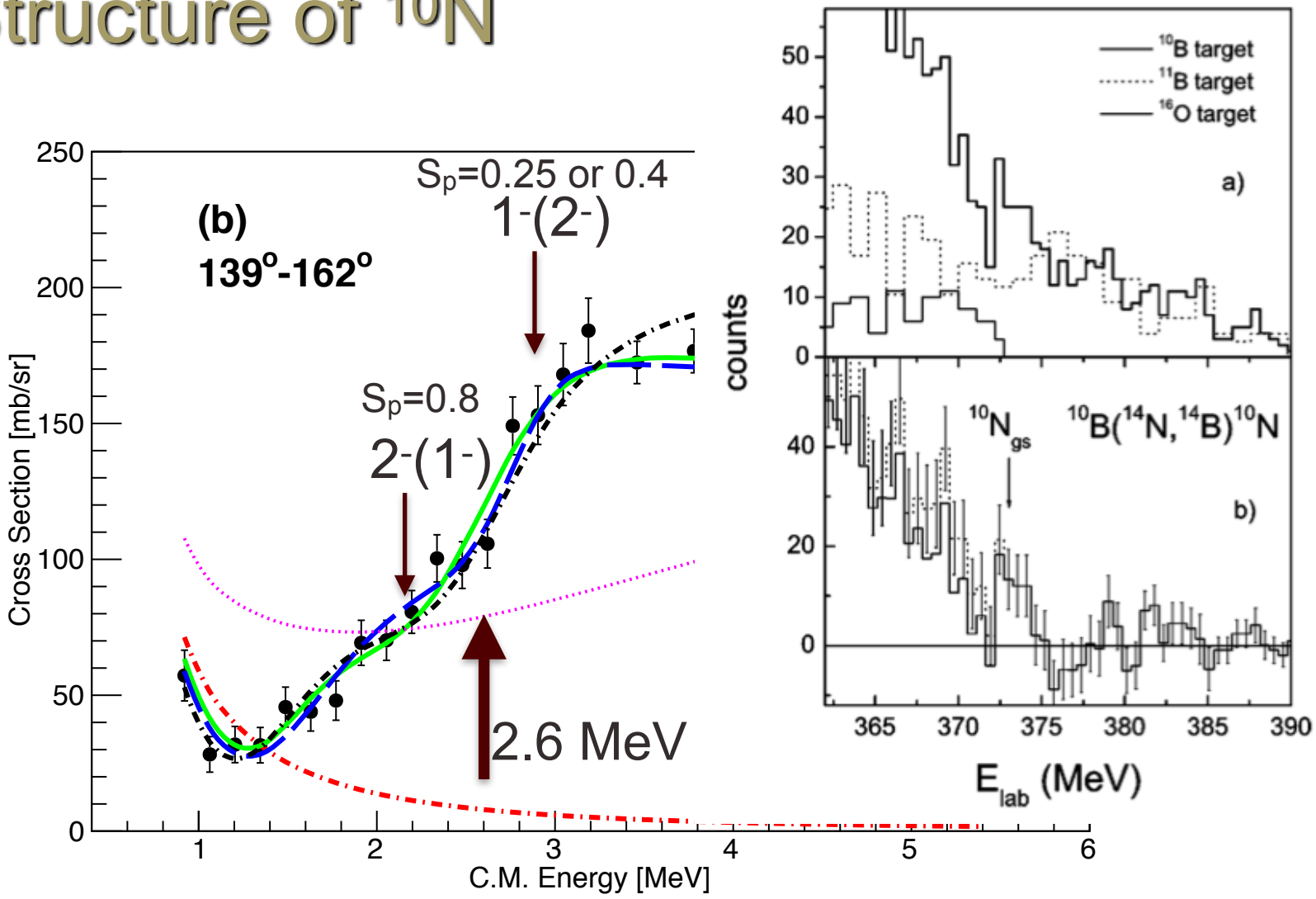
Structure of ^{10}N

Excitation function for ^{9}C+p elastic scattering



- ^{9}C beam at energy 8 MeV/u was produced by MARS separator at Texas A&M U.

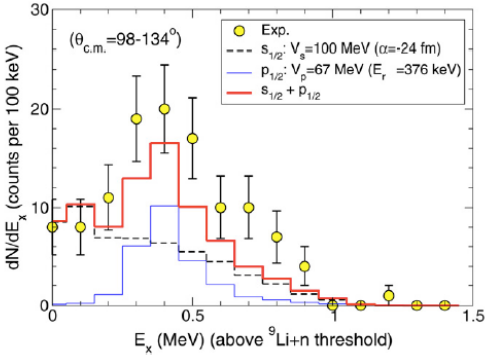
Structure of ^{10}N



- The only previous ^{10}N result - A. Lepine-Szily, et al., PRC 65 (2002): possible observation of a broad structure at 2.6 MeV

^{10}Li structure

^{9}Li(d,p)

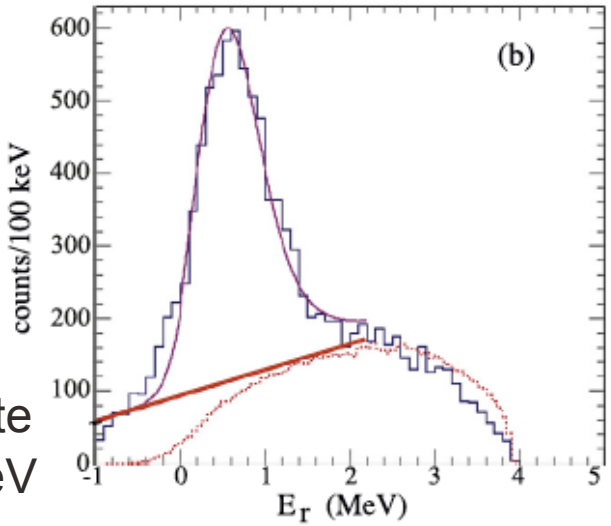


E=22 keV - virtual s-state

E=0.38 MeV, Γ=0.20 MeV

H.B. Jeppesen, et al.,
PLB 642 (2006) 449

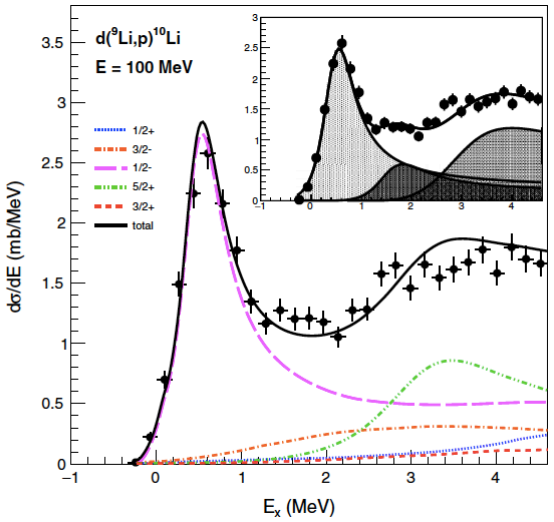
^{11}Li(p,d)



E=0.62 MeV, Γ=0.33 MeV

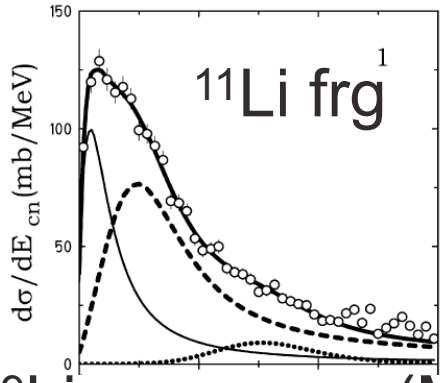
A.Sentullaev, et al.,
PLB 755 (2016) 481

^{9}Li(d,p)



E=0.45 MeV, Γ=0.68 MeV

M. Cavallaro, et al.,
PRL 118 (2017) 012701



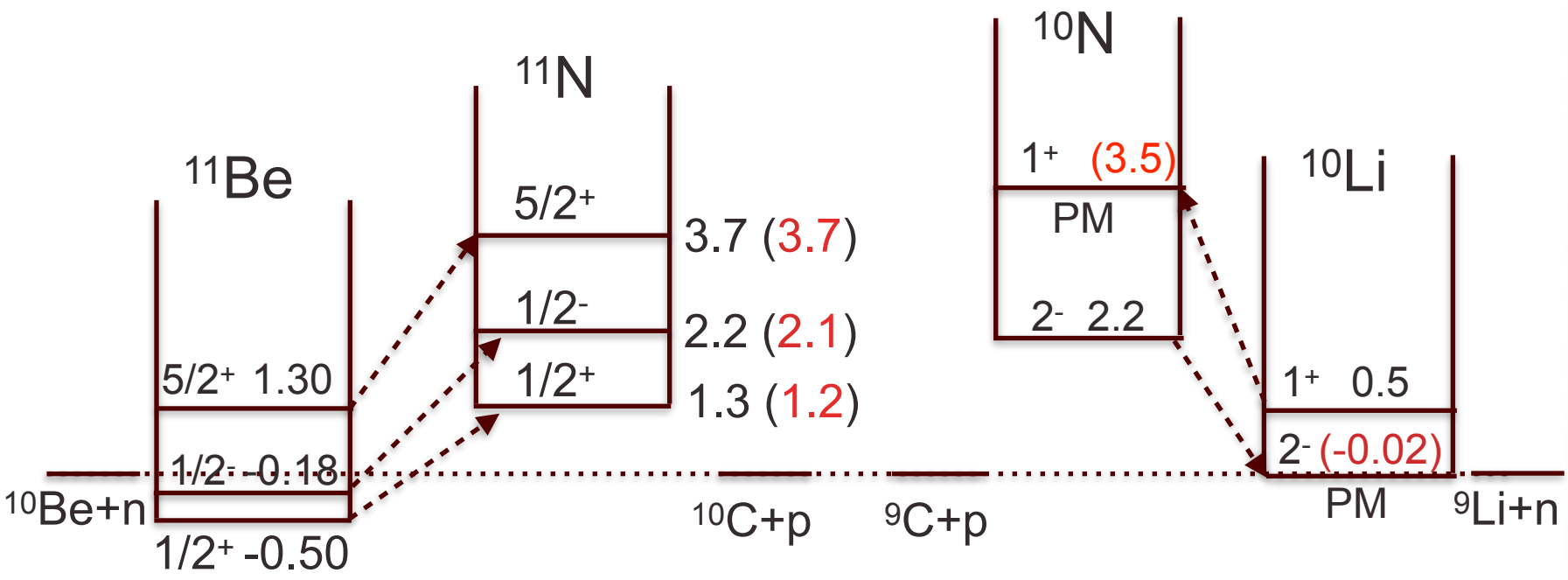
a = -30 fm - virtual s-state

E = 0.51 MeV, Γ=0.54 MeV

H. Simon, et al.,
Nucl. Phys. A 791 (2007) 267

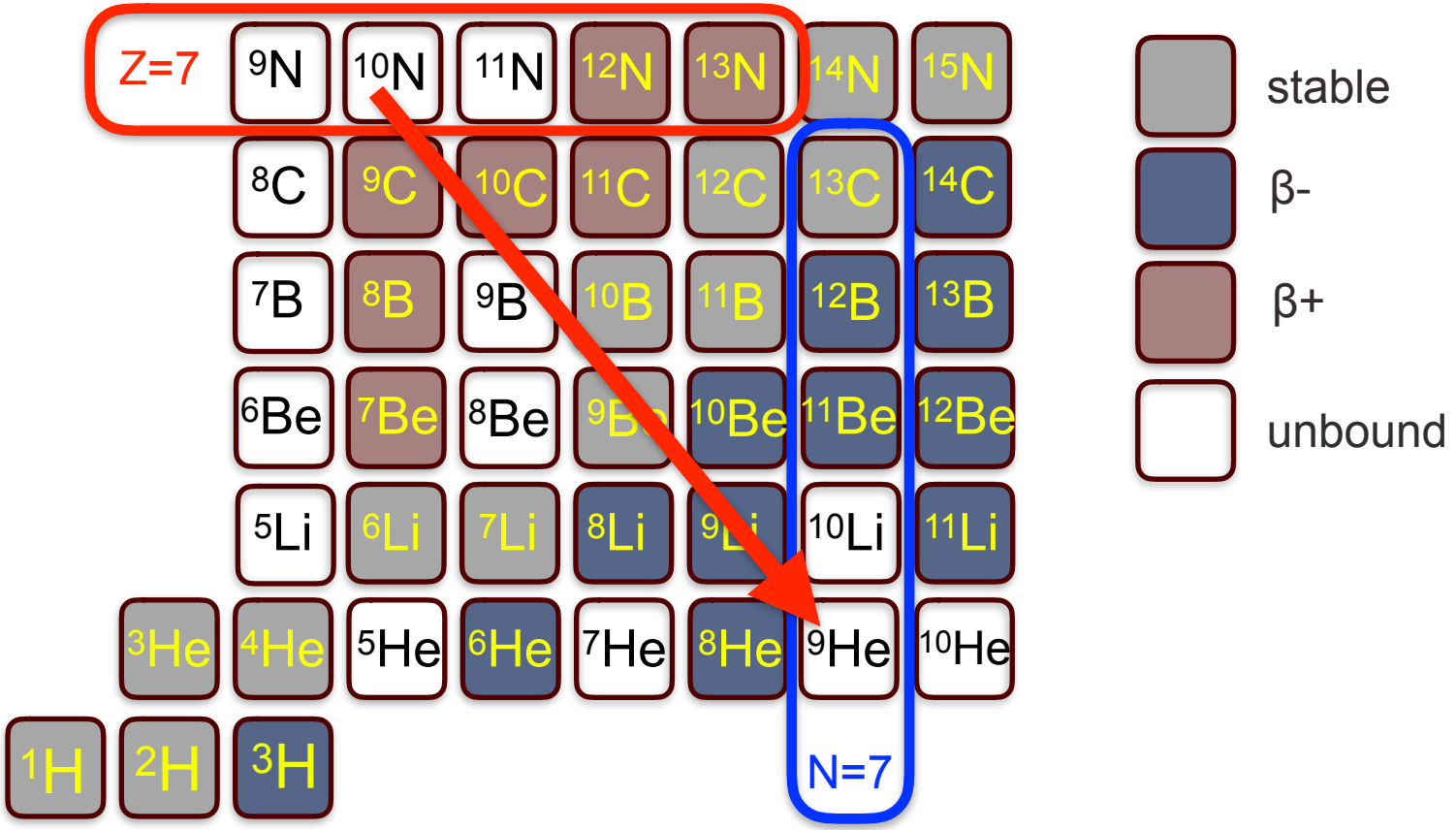
Potential model extrapolation

PM parameters: r_o = 1.25 fm, a=0.7 fm, r_c = 1.3 fm

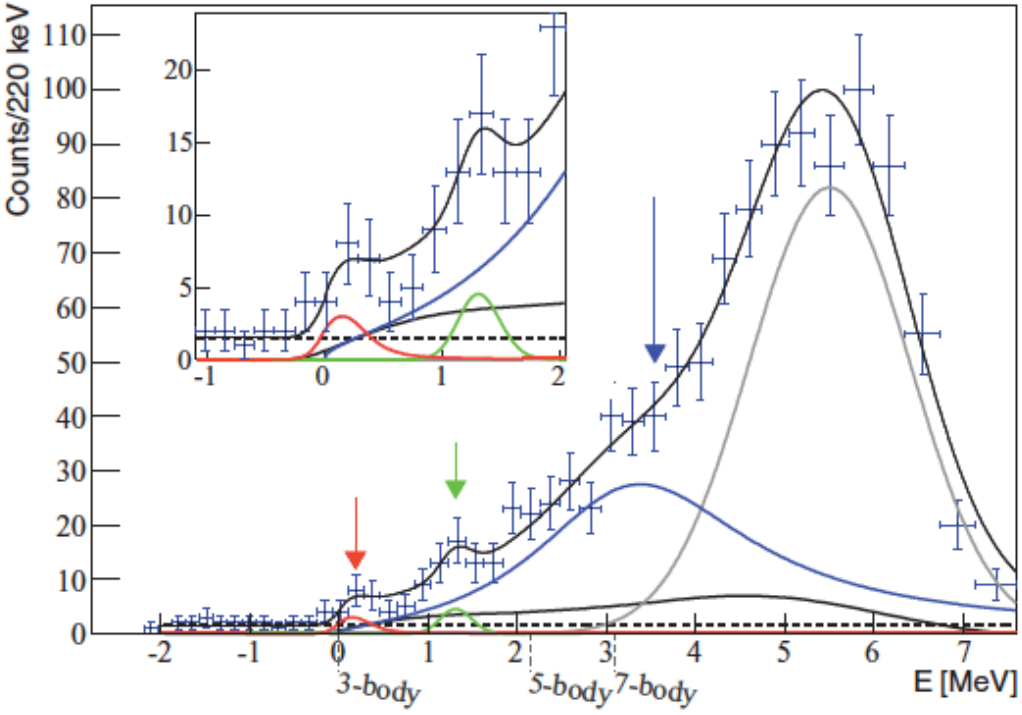


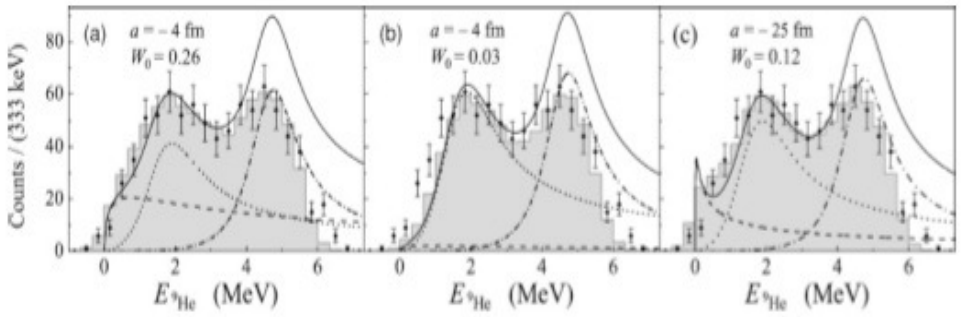
All values are in MeV. The experimental values for the known states are given. Potential model extrapolation are in parenthesis in red.

^{9}He


Z=7
9N 10N 11N 12N 13N 14N 15N
8C 9C 10C 11C 12C 13C 14C
7B 8B 9B 10B 11B 12B 13B
6Be 7Be 8Be 9Be 10Be 11Be 12Be
5Li 6Li 7Li 8Li 9Li 10Li 11Li
3He 4He 5He 6He 7He 8He 9He 10He
1H 2H 3H
N=7
stable
β-
β+
unbound

Previous results for ^{9}He





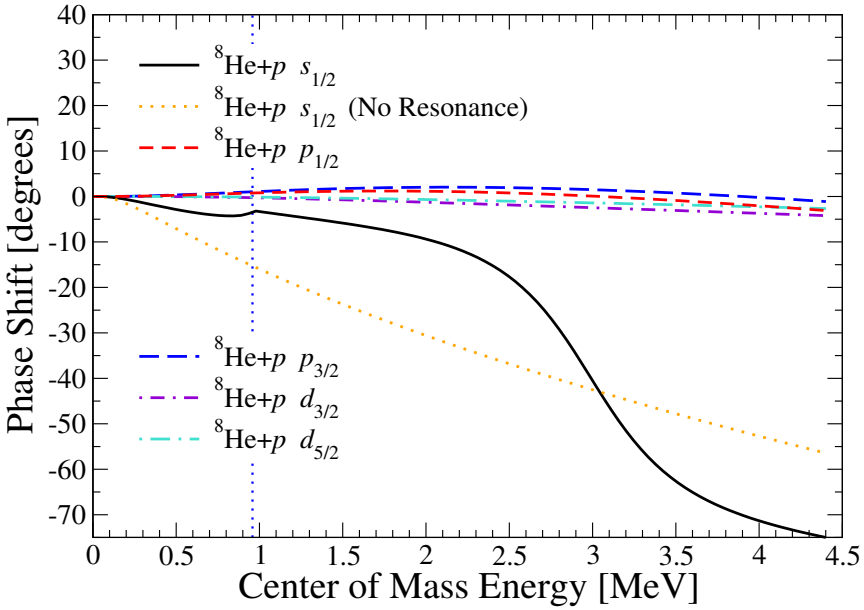
- Recent ^{8}He(d,p) measurements indicate low lying $1/2^{+}$ and $1/2^{-}$ states

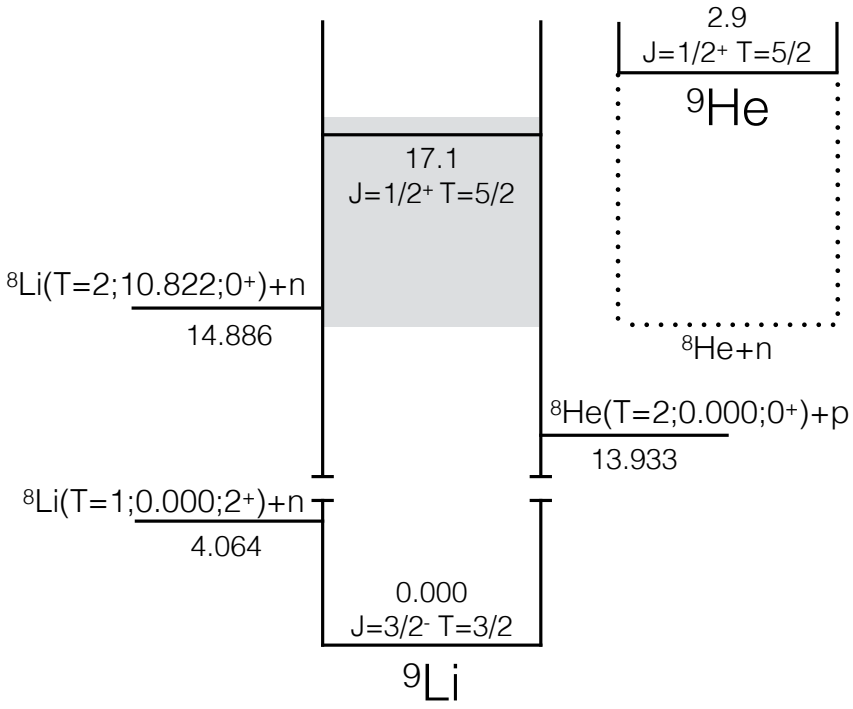
  T.Al. Kalanee, et al., PRC 88 (2013) 034301

- This contradicts earlier ^{8}He(d,p) data

M.S. Golovkov, et al., PRC 76 (2007) 021605

Level structure of ^{9}He inferred from the ^{8}He+p measurements and the phase shifts





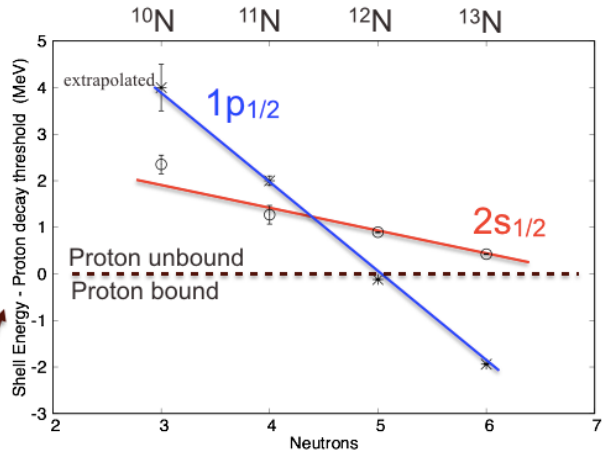
PHYSICAL REVIEW C **89**, 061305(R) (201

Neutron *s* states in loosely bound n

C. R. Hoffman, B. P. Kay, and J. P. Schif

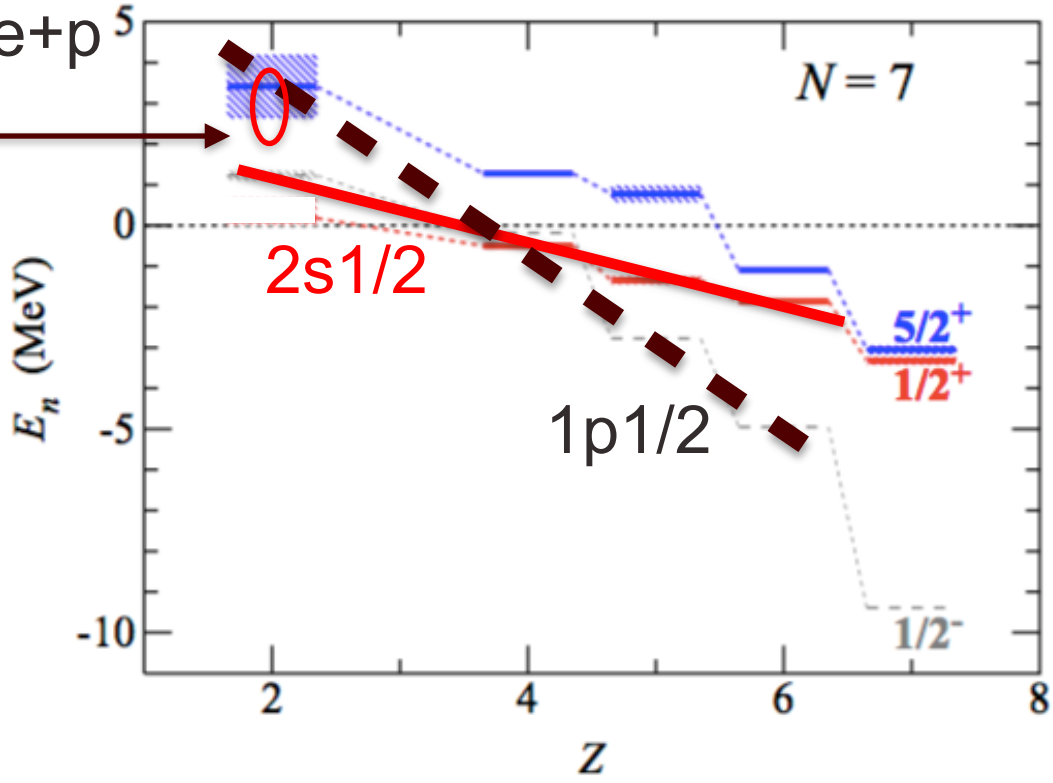
Physics Division, Argonne National Laboratory, Argonne, Il

(Received 6 November 2013; revised manuscript received 13 May 201



9He 10Li 11Be 12B 13C

From 8He+p phase shift analysis



Acknowledgement

- ***Texas A&M University:*** G. Chubarian, V.Z. Goldberg, ***J. Hooker***, C. Hunt, E. Koshchiy, H. Jayatissa, D. Melconian, B. Roeder, ***E. Uberseder***, A. Saastamoinen, A. Spiridon, R.E. Tribble.
- ***TRIUMF:*** M. Alcorta, B. Davids