Structure of light nuclei and modern theory
(In resonance scattering with rare isotope beams)

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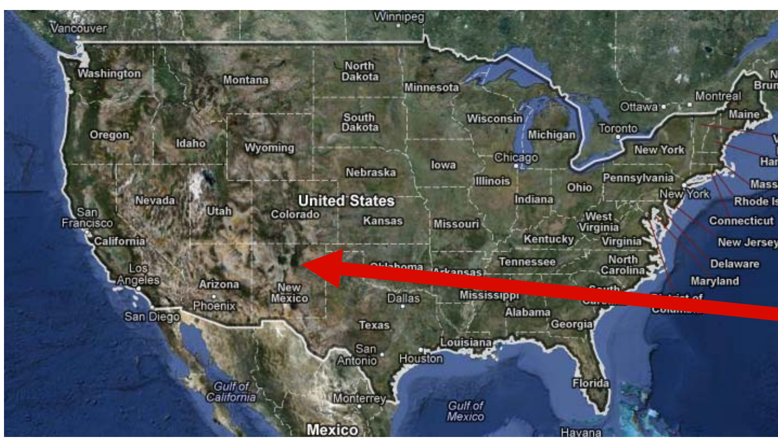
Outline

- Thick Target Inverse Kinematics Method for Resonance Scattering induced by Rare Isotope Beams
- Structure of light nuclei and modern theory
- Resonance scattering induced by rare beams and alpha clusters
- Summary

МГУ 18 июня 2013

- National Research Center “Kurchatov Institute”.
- Before 1962 known under secret name of Laboratory #2. The place where the Soviet nuclear weapons program have started.



Laboratory #1 ???

TEXAS A&M UNIVERSITY.

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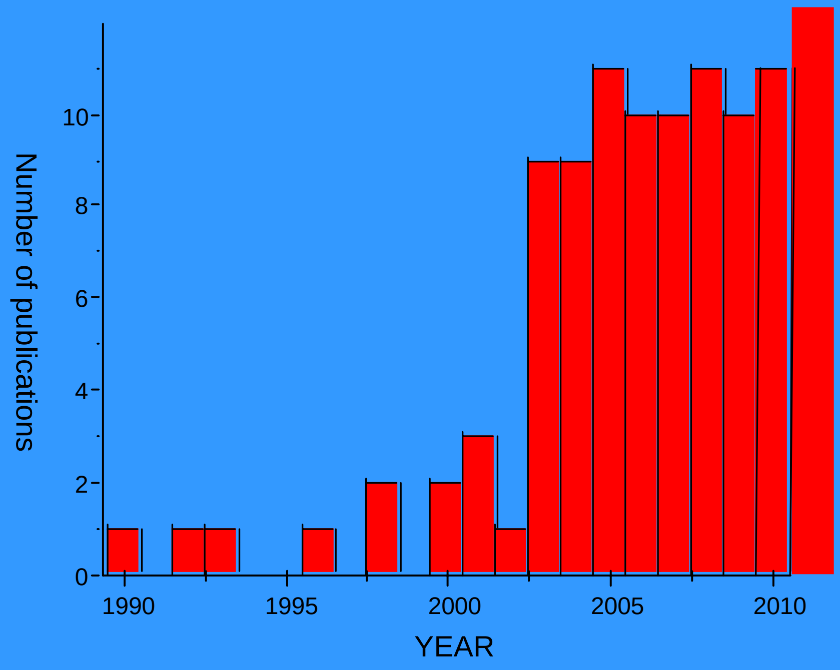
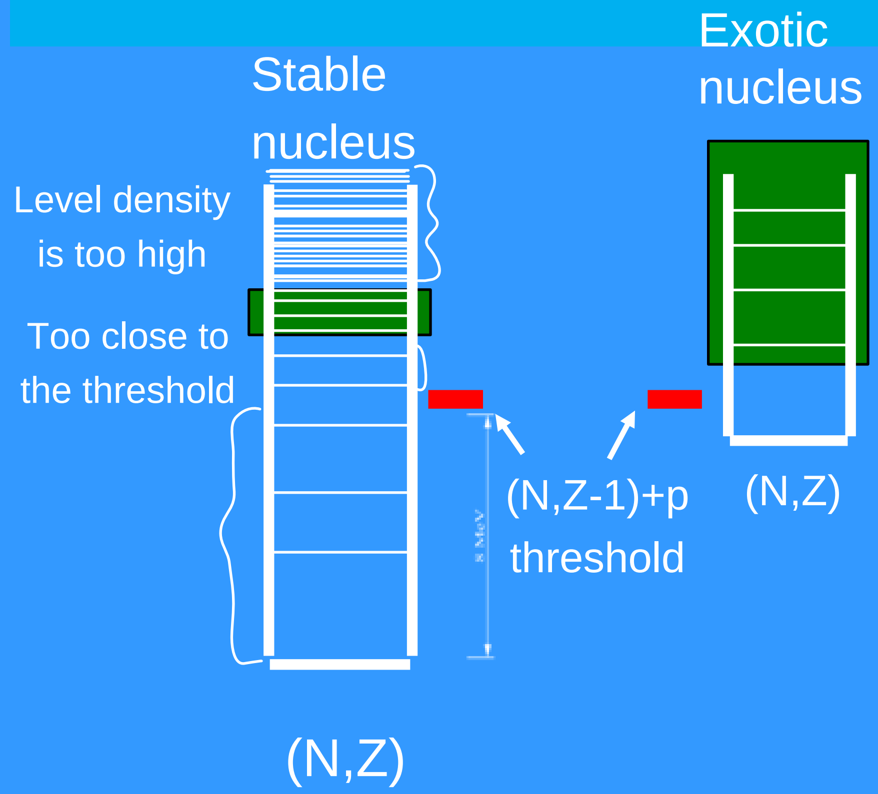
Progress in Thick Target Inverse Kinematics Studies (publications)

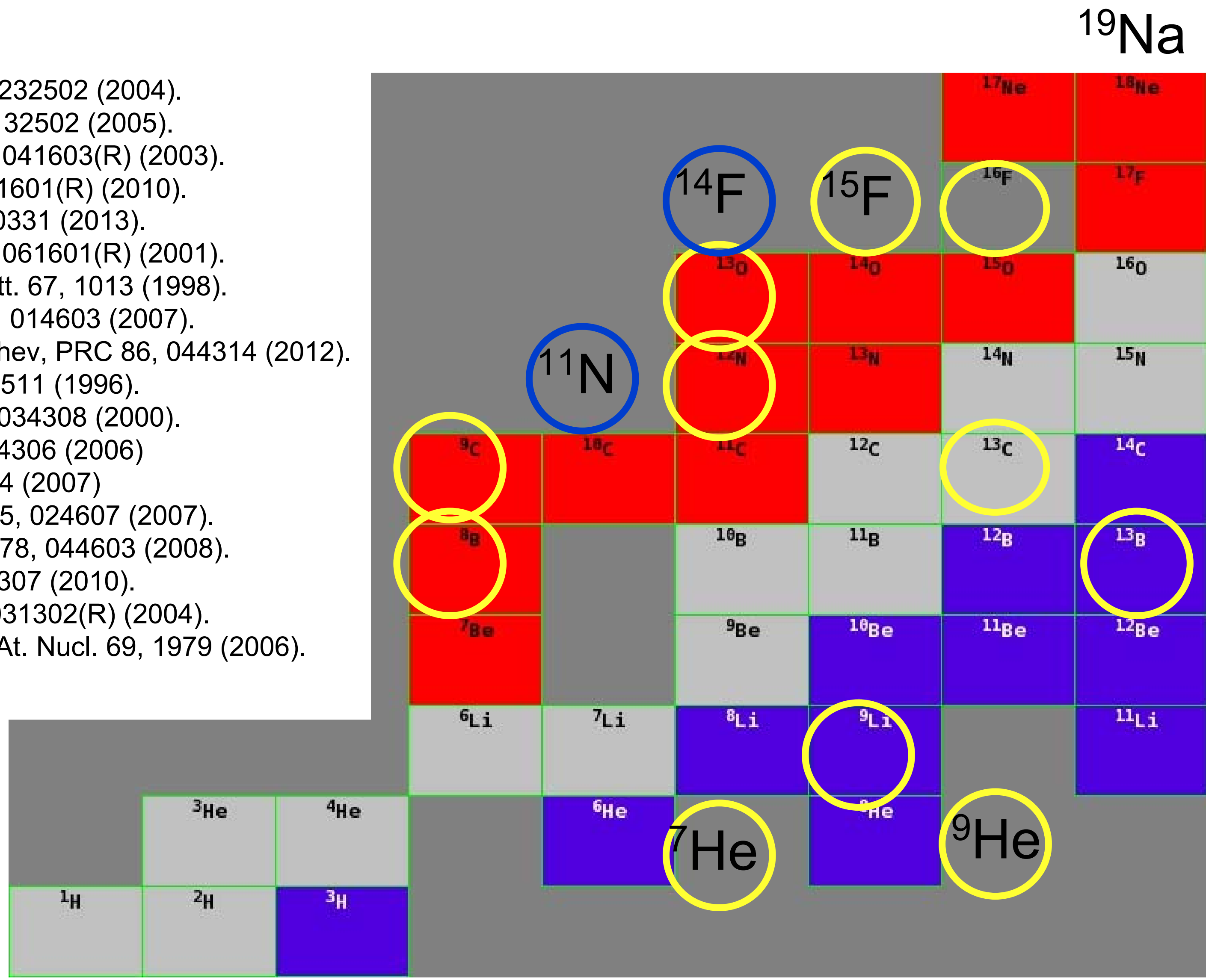


Resonance reactions with rare beams provide for access to low lying state in exotic nuclei.



The field of the investigation

G.V. Rogachev et al., PRL 92, 232502 (2004).
P. Boutachkov et al., PRL 95, 132502 (2005).
G.V. Rogachev et al., PRC 67, 041603(R) (2003).
J.P. Mitchell et al., PRC 82, 011601(R) (2010).
J.P. Mitchell et al., arXiv:1303.0331 (2013).
G.V. Rogachev et al., PRC 64, 061601(R) (2001).
V.Z. Goldberg, et al., JETP Lett. 67, 1013 (1998).
G. V. Rogachev et al., PRC 75, 014603 (2007).
V.Z. Goldberg and G. V.Rogachev, PRC 86, 044314 (2012).
L. Axelsson, et al., PRC 54, R1511 (1996).
K. Markenroth, et al., PRC 62, 034308 (2000).
K. Perajarvi, et al., PRC 74, 024306 (2006)
D.W. Lee et al, PRC 76, 024314 (2007)
B.B. Skorodumov et al., PRC 75, 024607 (2007).
B.B. Skorodumov, et al., PRC 78, 044603 (2008).
V.Z. Goldberg et al., PLB 692, 307 (2010).
V.Z. Goldberg et al., PRC 69, 031302(R) (2004).
B.B. Skorodumov et al., Phys. At. Nucl. 69, 1979 (2006).

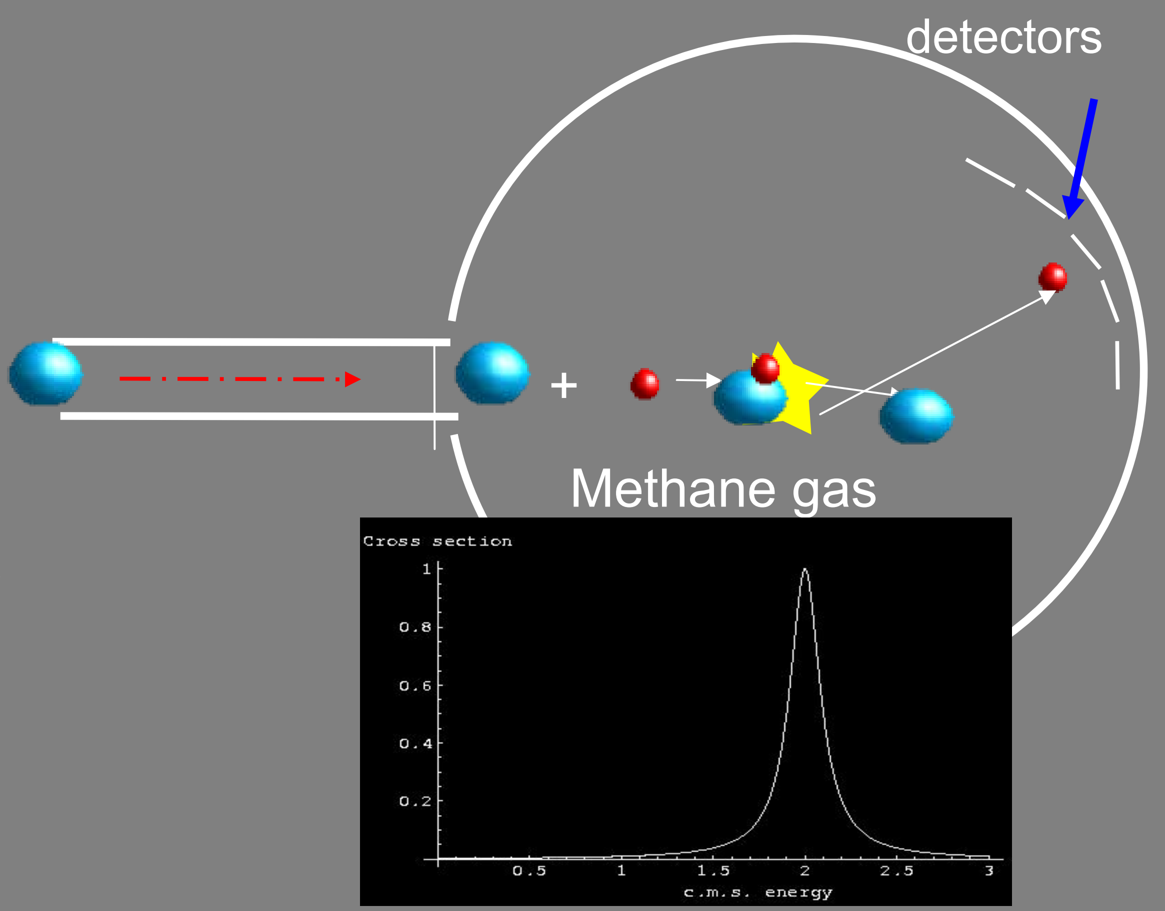


Inverse geometry and thick target technique

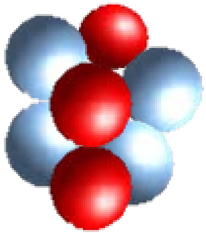
[Yad.Fiz. 52, 634 (1990); Sov.J.Nucl.Phys. 52, 408 (1990)]

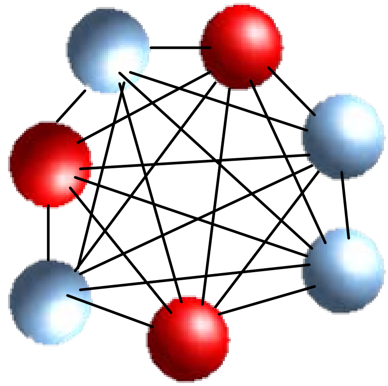
Scattering chamber

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

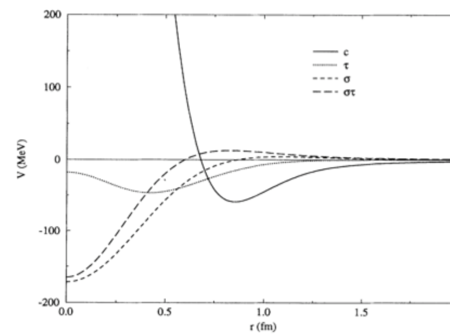


Ab Initio Approach





AV$_{18}$



R. Wiringa, et al., PRC 51 (1995) 38

$$H = T + V = \sum_{i=1}^{A} \frac{-\hbar^2}{2m_N}\nabla_i^2 + \sum_{i,j=1(i<j)}^{A} v(r_i, r_j)$$

- $v(r_i,r_j)$ is bare nucleon-nucleon interaction determined from large body of experimental data on nucleon-nucleon scattering, and deuteron binding energy.

Methods to solve (numerically) the many-body SE for atomic nuclei without introducing mean field have been developed during the last 15 years. No Core Large Basis Shell Model (NCSM), Variational Monte Carlo (VMC), Greens Function Monte Carlo (GFMC) and Chiral Effective Field Theory and Monte Carlo Lattice Simulations (ChEFT) methods are the prime examples.

Challenges of ab Initio Approach

- The nucleon-nucleon interaction is not unique.
- The "free" nucleon-nucleon interaction and nucleon-nucleon interaction in nuclear medium is not the same thing.
- Calculations are notoriously difficult, labor and time consuming.
- Truncation is still necessary.
- Three body (four body?) interactions appear to play an important role!
- Only light nuclei can be studied at present.

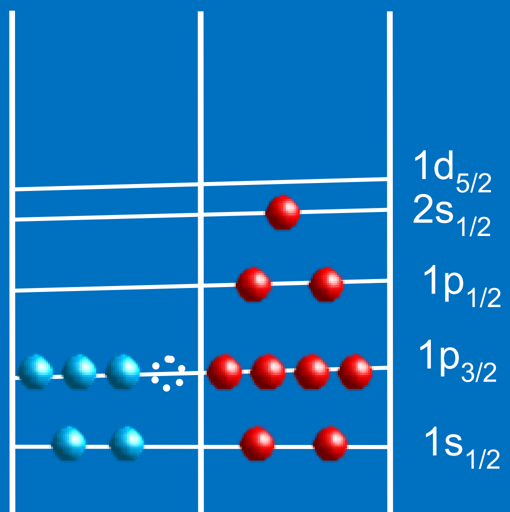
$$H = T + V = \sum_{i=1}^{A} \frac{-\hbar^2}{2m_N}\nabla_i^2 + \sum_{i,j=1(i<j)}^{A} v(r_i, r_j) + \sum_{i,j,k=1(i<j<k)}^{A} v(r_i, r_j, r_k)$$

New nuclide, ^{14}F

Proton Drip line

		^{16}Ne −1.4	^{17}Ne +1.5	^{18}Ne +3.9	^{19}Ne +6.4	^{20}Ne +12.8
	^{14}F?	**^{15}F −1.5**	^{16}F −0.54	^{17}F +0.6	^{18}F +5.6	^{19}F +7.9
^{12}O −1.8	^{13}O +1.5	^{14}O +4.6	^{15}O +7.3	^{16}O +12.1	^{17}O +13.8	^{18}O +15.9

Black – Stable
Pink – EC or β^+ Decay
Yellow – p Decay



^{14}F

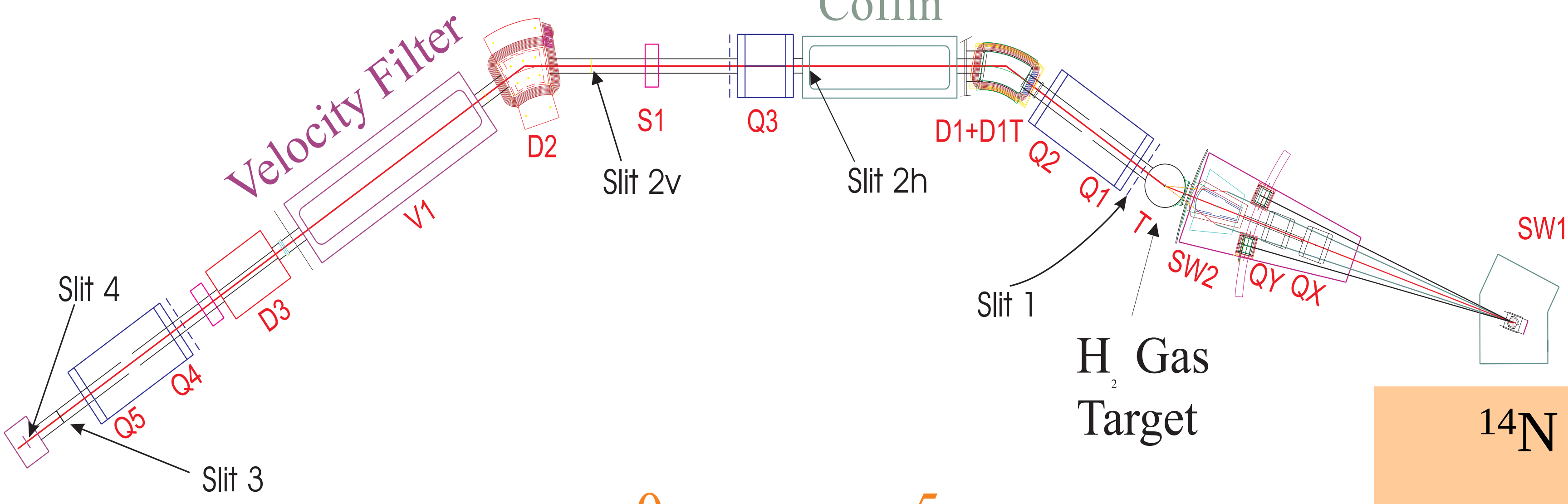
G.C. Ball, et al., PRL **31**, 395 (1973) extrapolation
F. Ajzenberg-Selove, NPA 523, 1 (1991). extrapolation
G. Audi, et al., NPA 729, 337 (2003). Extrapolation
P.Maris, A.M. Shirokov, J.P. Vary PRC 81, 021301(R)(2010)

^{14}F instability to proton decay is ~3 MeV

*An evident experimental solution is to add a proton to **^{13}O***

Momentum Achromat Recoil Separator {MARS}

^{13}O beam



^{14}N

38MeV/u

^{13}O 8.58 • 0.05 ms

31MeV/u

0 5

Scale (meters)

It should be expected that a beam of extreme drip-line nuclei (like ^{13}O) will be rather high energy beam and be obtained using in-flight separation.

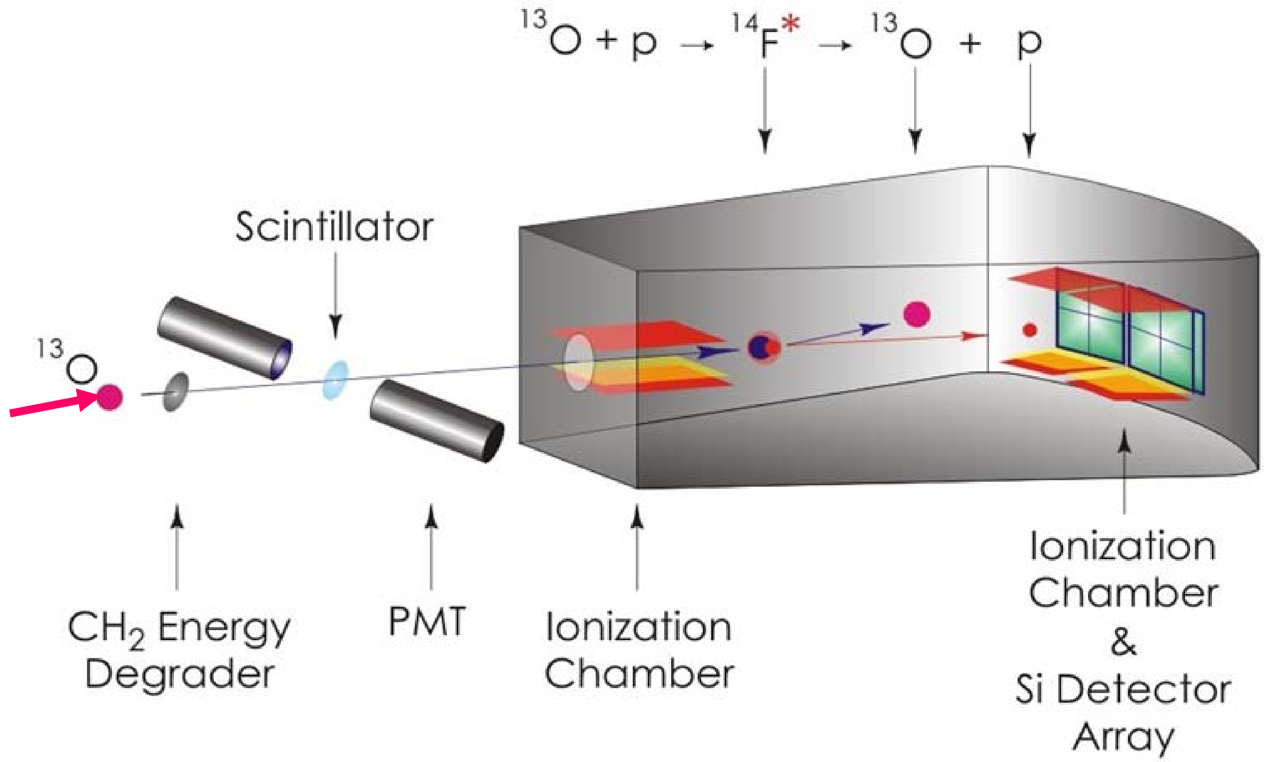
- **Primary beam ^{14}N@ 38 MeV/A – K500 Cyclotron**
- **Primary target LN$_2$ cooled gas target H$_2$ p=3.0 atm**

Secondary beam 13O @ 31 MeV/A
Purity: ~90% Intensity: ~4x10^{3}pps

Texas A&M University

Setup of the experiment

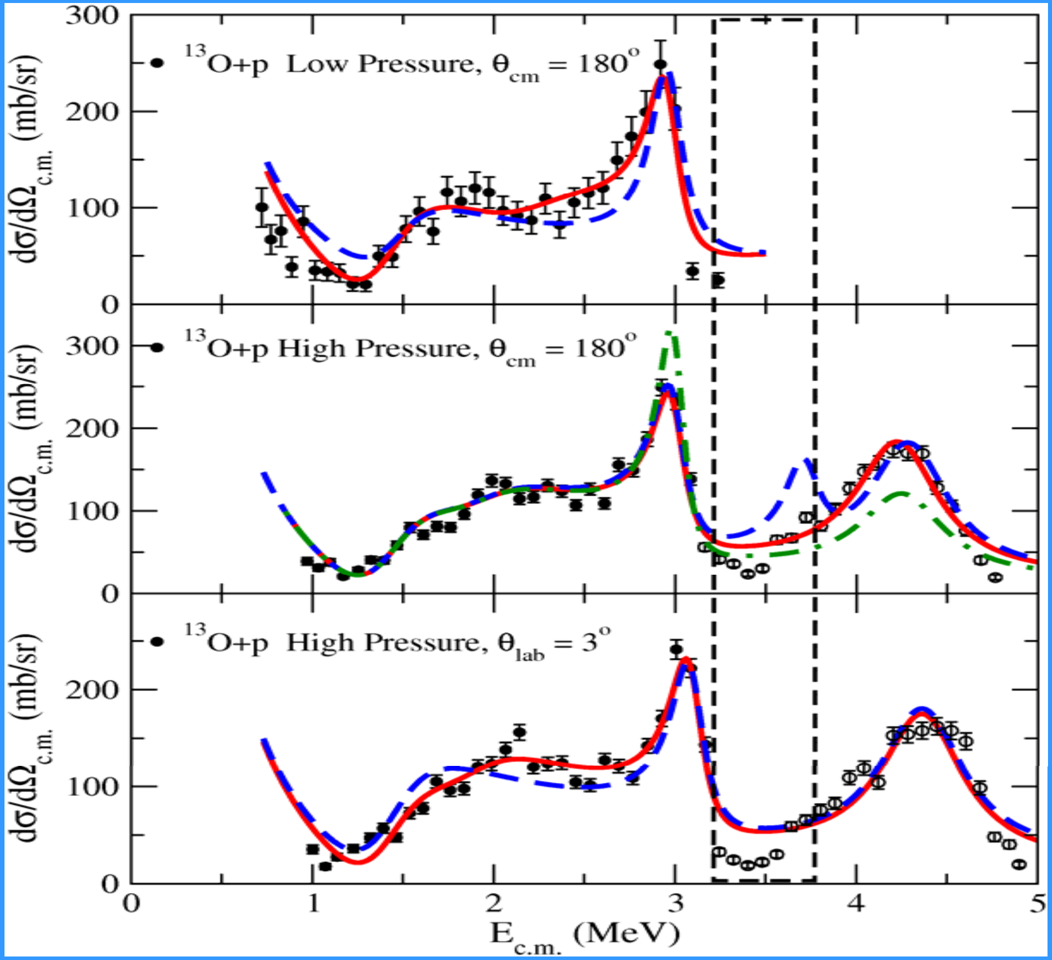
for Thick Target Inverse Kinematics Resonant Scattering



Heavy ions deposit their energy in the matter containing light elements (hydrogen or helium). A resonance manifests itself by a rapid increase of the recoil yield at the corresponding energy.

V.Z. Goldberg, et al., Phys. Lett. B 692 (2010) 307

Excitation functions for the ^{13}O+p elastic scattering



The solid line is the best fit.

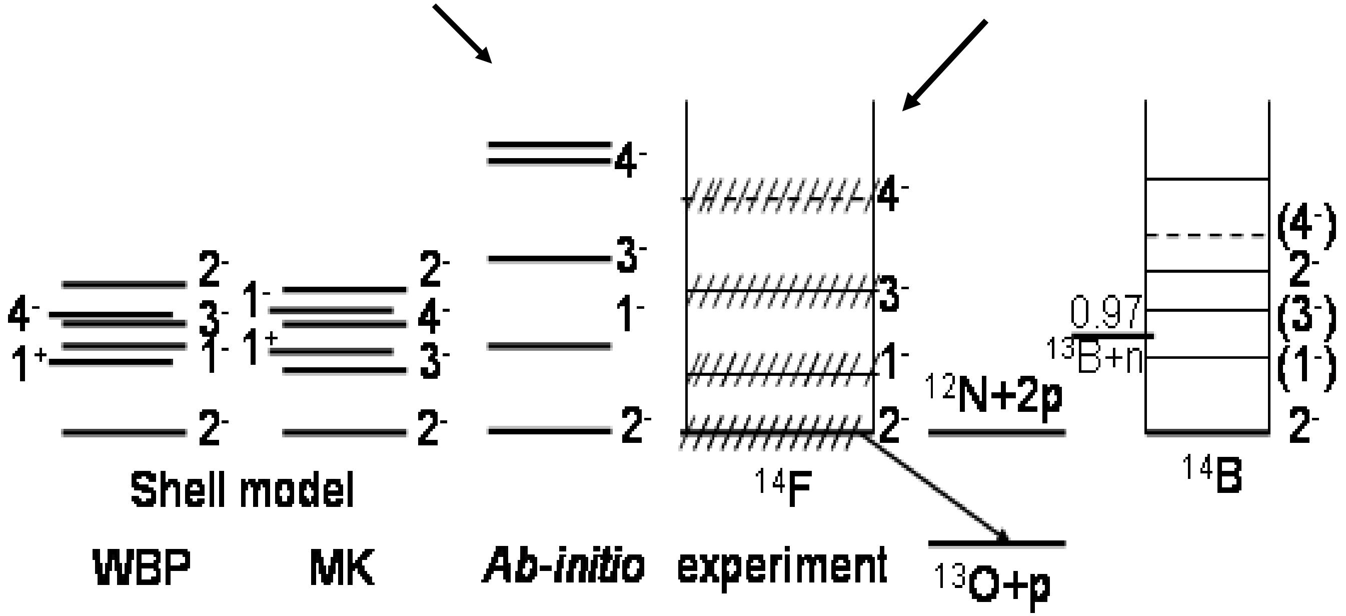
The dashed line (blue) is a fit with 1^- as the ground state (instead of 2^-).

The dashed line (blue) is calculation with a second hypothetical 2^- state at high energy. The dashed-dot line is a calculation with a $4-$ state at 3 MeV (instead of 3^-) and a 3^- state at 4.35 MeV (instead of 4^-).

The dashed line is the fit without the 1^- first excited state.

P. Maris, A.M. Shirokov, J.P. Vary, PRC **81**, 021301(R) (2010)-JISP16

V.Z. Goldberg, et al., Phys. Lett.. B 692 (2010) 307



Prediction for the $^{14}F_{gr.st}$ was: E_R=3 MeV

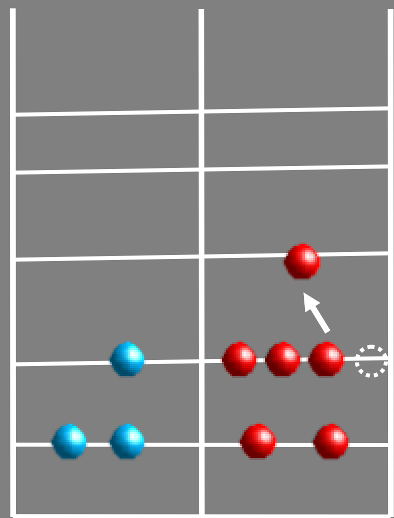
^{14}F Summary

- First experimental data on the level scheme in ^{14}F (the intensity of the ^{13}O beam was~3×10^3 p/s) generally agree with the results of *ab initio* calculations
- However ^{14}F appeared to be less unstable (~1.5 MeV) than was expected.
- The unexpected gain in stability of ^{14}F is mainly related with the surprising purity of its single particle structure.

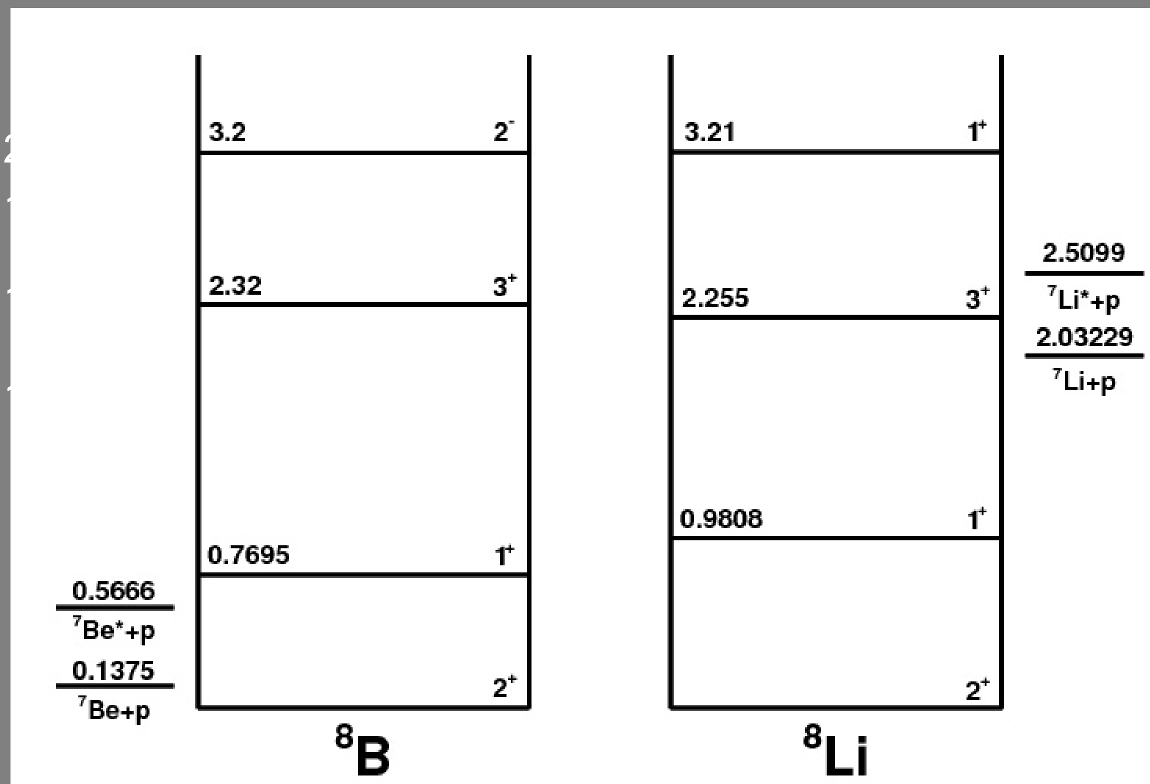
Would you believe that there are the unknown low laying levels in the lightest nuclei?

$$3/2^- \otimes 3/2^- = 0^+;\ 1^+;\ 2^+;\ 3^+$$

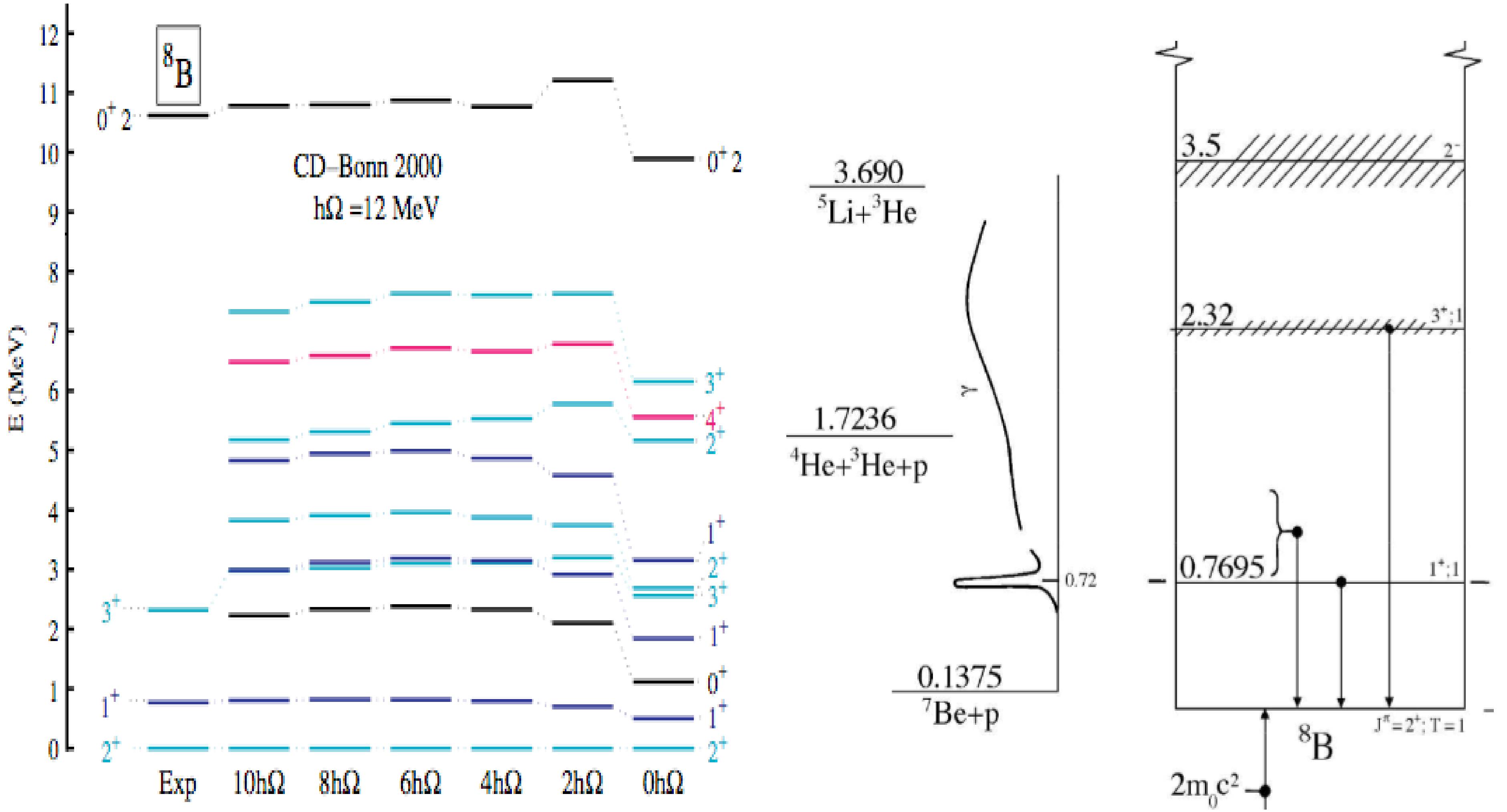
$$3/2^- \otimes 1/2^- = 1^+;\ 2^+$$



^{8}B



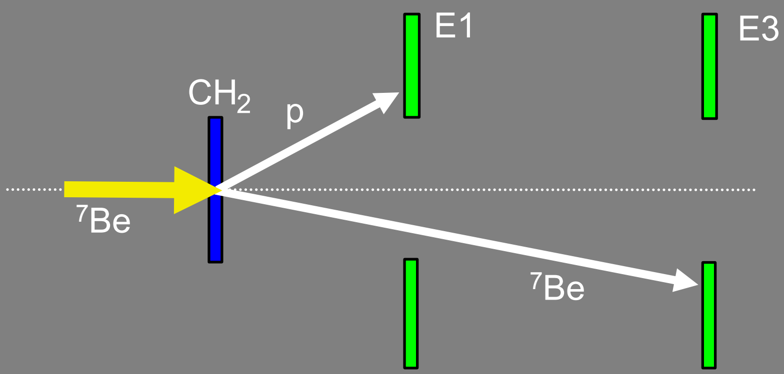
Structure of ^8B

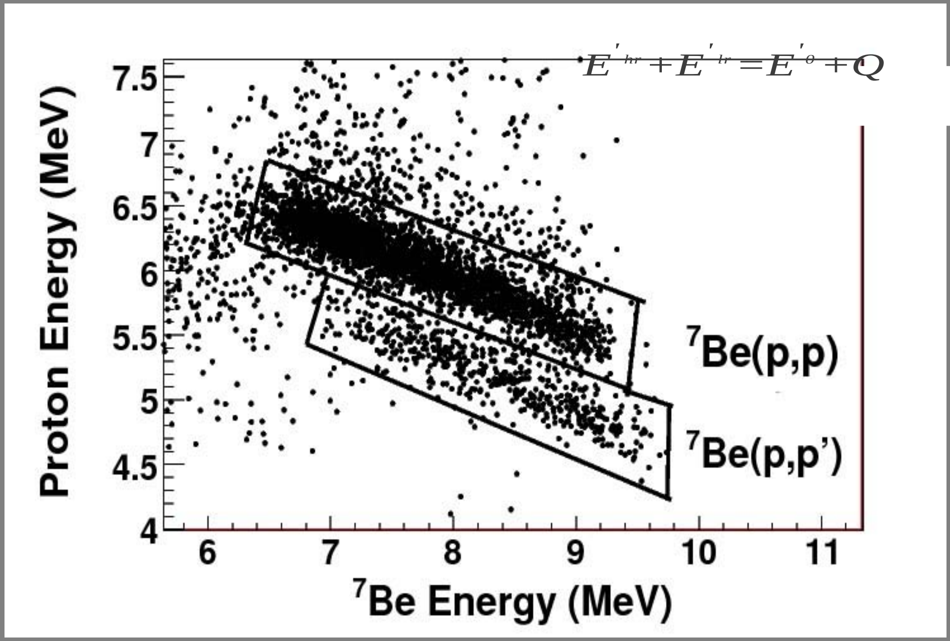


P. Navratil, et al., PRC 73, 065801 (2006)

Hybrid (thick/thin) target technique

- Target is thick enough for ^{7}Be to lose significant fraction of it's energy.
- But thin enough for ^{7}Be recoils to make it out of the target.



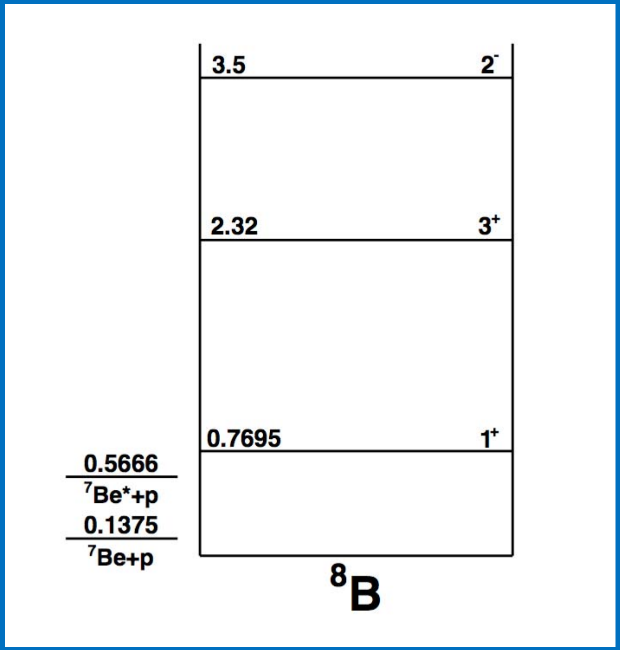


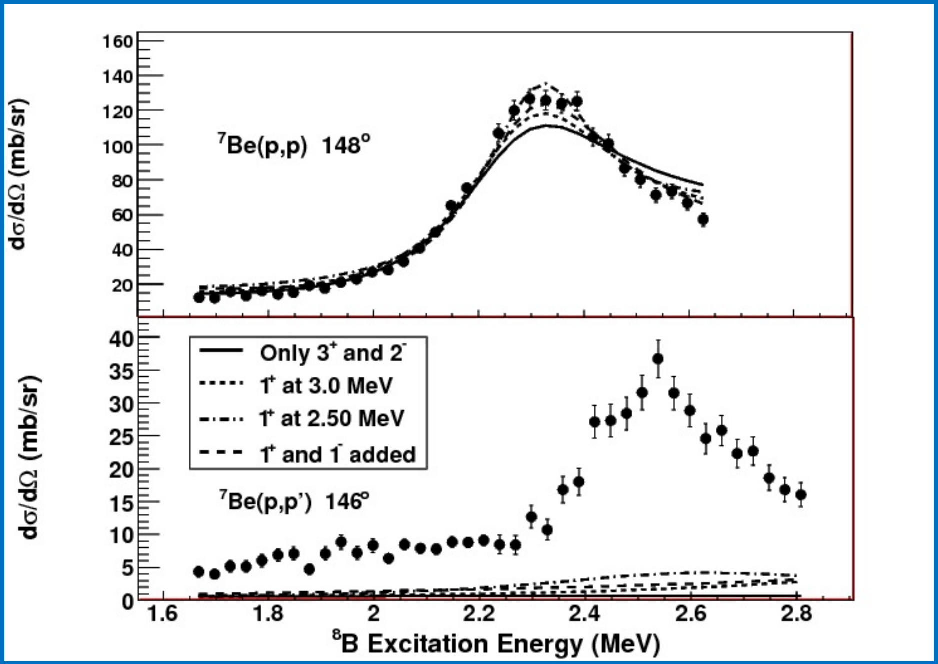
Courtesy of Dr. G. Rogachev

Known 3^+ and 2^- states CANNOT explain high inelastic cross section!

$^8B(3^+) \Rightarrow {}^7Be(3/2^-, g.s.) + p$ with L=1
$^8B(3^+) \Rightarrow {}^7Be(1/2^-, 0.43) + p$ with L=3

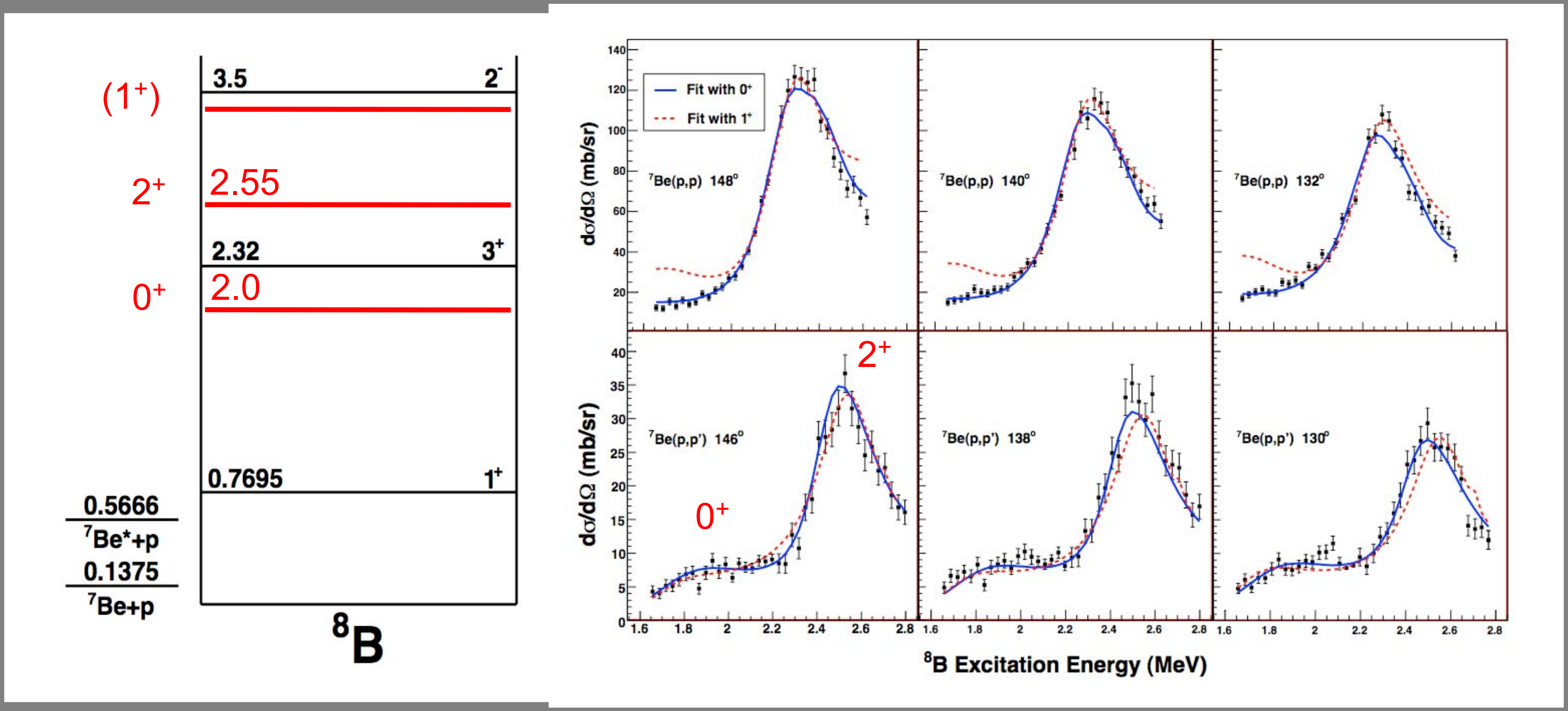
$^8B(2^-) \Rightarrow {}^7Be(3/2^-, g.s.) + p$ with L=0
$^8B(2^-) \Rightarrow {}^7Be(1/2^-, 0.43) + p$ with L=2





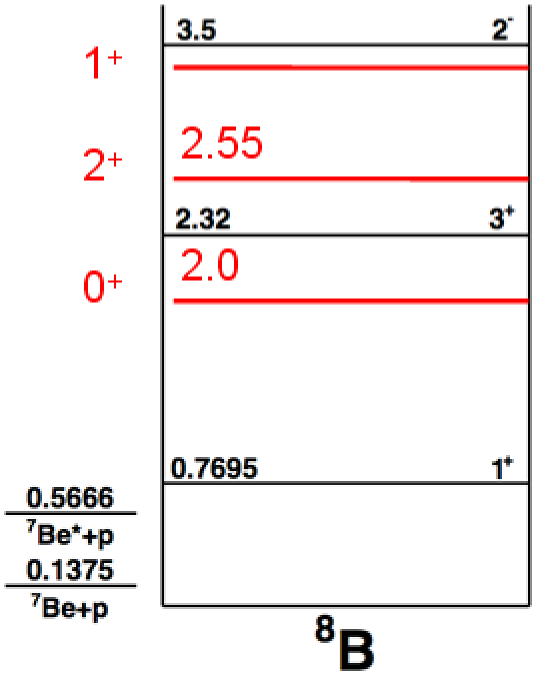
Courtesy of Dr. G. Rogachev

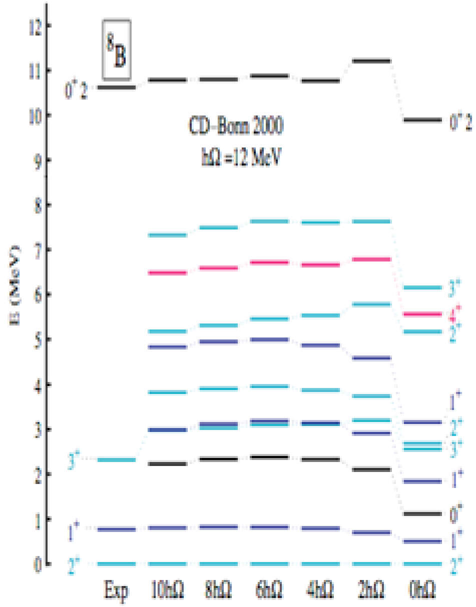
R-matrix fit requires new 0^+ and 2^+ states at 2.0 MeV and 2.55 MeV in ^{8}B.



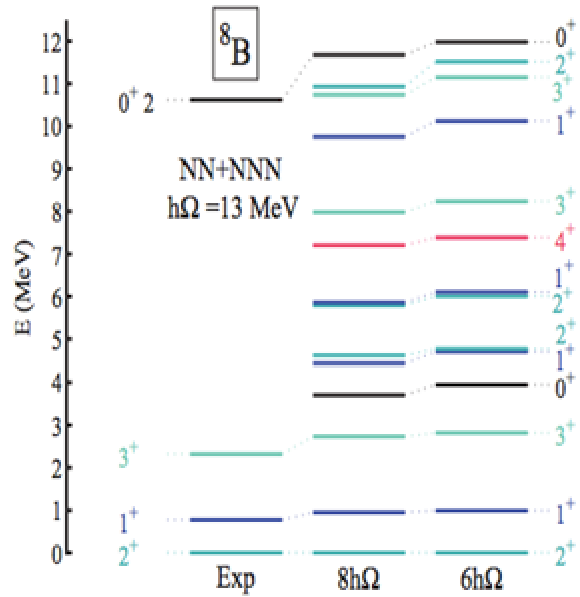
J.P. Mitchell, et al., PRC 82, 011601(R) (2010)
PRC (2013)

Structure of ^{8}B



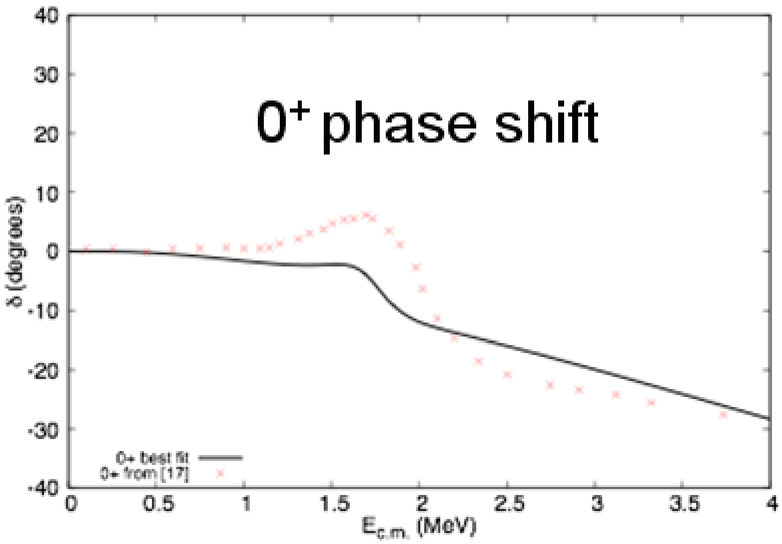


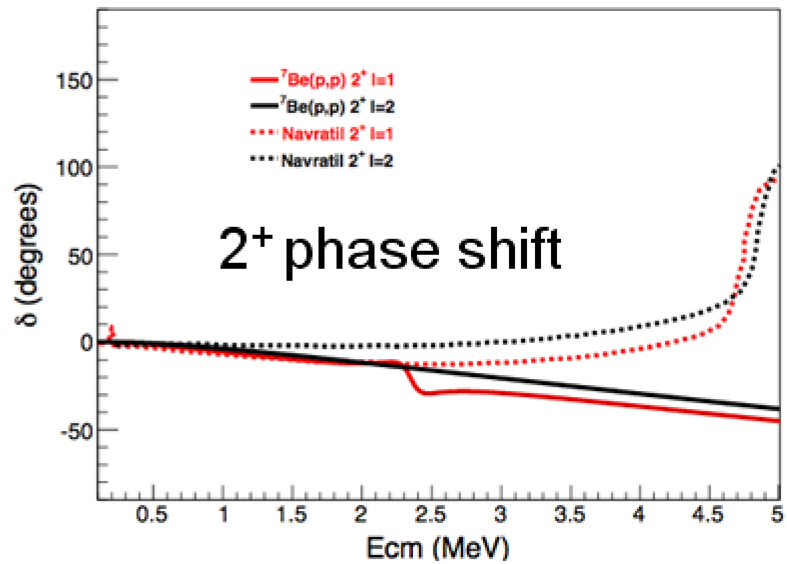
P. Navratil, et al.,
PRC 73, 065801 (2006)
NCSM calculations with
CD-Bonn 2000 interaction



P. Maris, et al.,
PRC 87, 014327 (2013)
NCSM calculations with
Chiral EFT NN+NNN
interaction (χEFT)

Structure of ^{8}B





Comparison of the ab initio NCSM/RGM [P. Navratil, et al., PRC82 034609 (2010)] phase shifts with experiment for the new low-lying states in ^{8}B

J.P. Mitchell, GR, et al., arXiv:1303.0331 (2013).

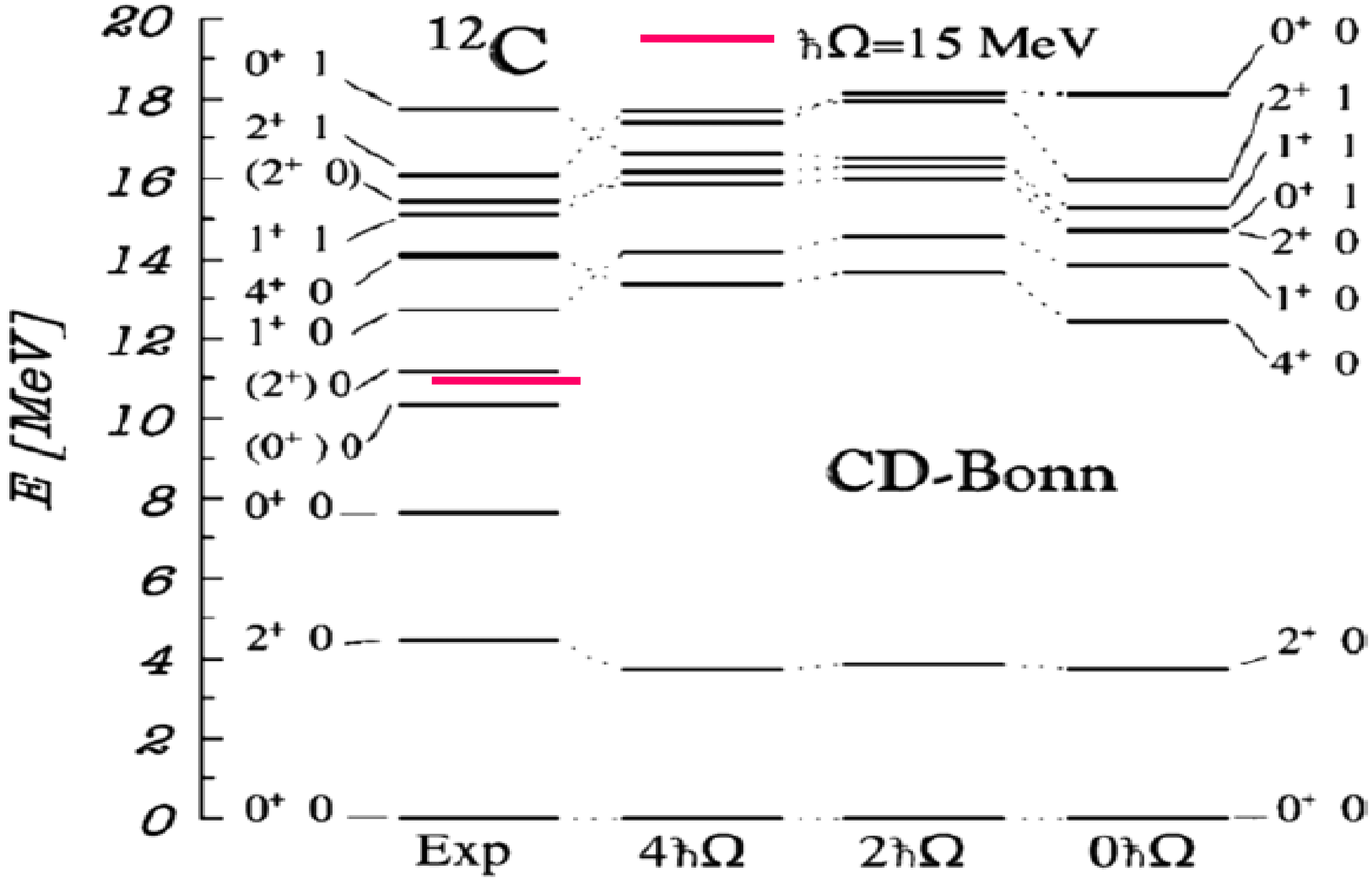
^{8}B Summary

- Study of the $^{7}Be+p$ elastic and inelastic resonant scattering resulted in observation of new low laying levels: 0^{+} and 2^{+}
- While the the levels were predicted by the *ab initio* calculations the specific properties of the levels in disagreement with the theory.

Navr″atil P, Vary J P and Barrett B R

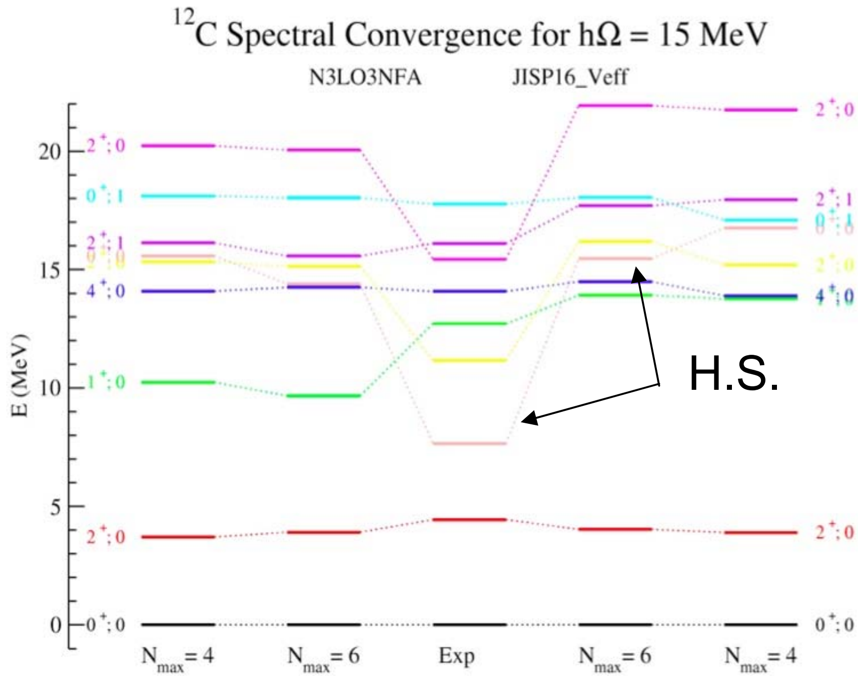
α-clusters and r/a beams

Phys. Rev. Lett. **84** 5728 (2000)

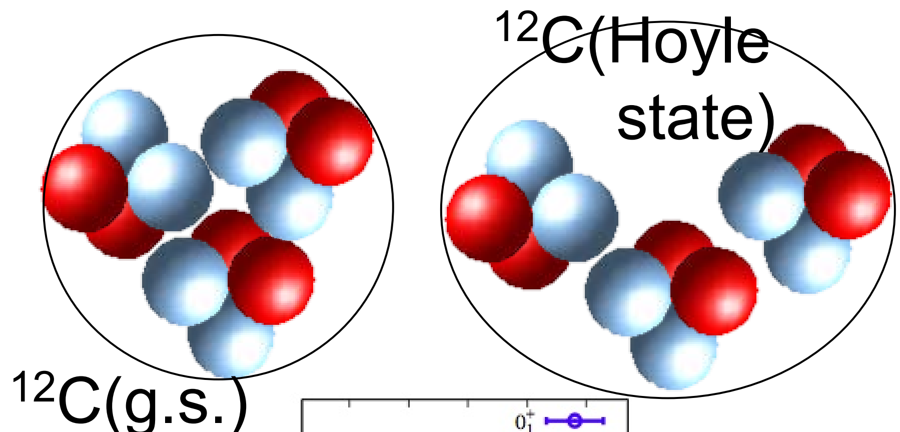


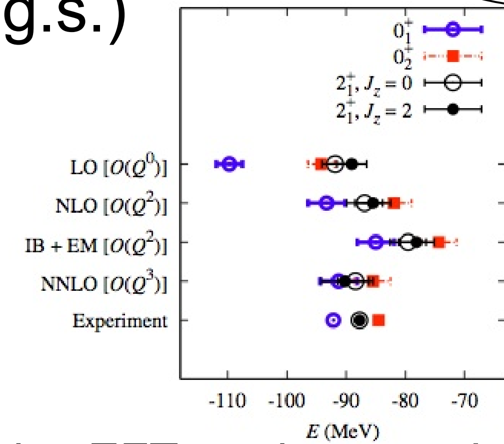
The no core shell-model calculations for the ^{12}C nucleus. The left hand part of the figure shows the experimental results. The calculations using the CD Bonn *N–N* interaction with increasing numbers of oscillator orbits are shown on the right.

Alpha Clusters



A.M. Shirokov, et al., PRC 79, 014308 (2009)





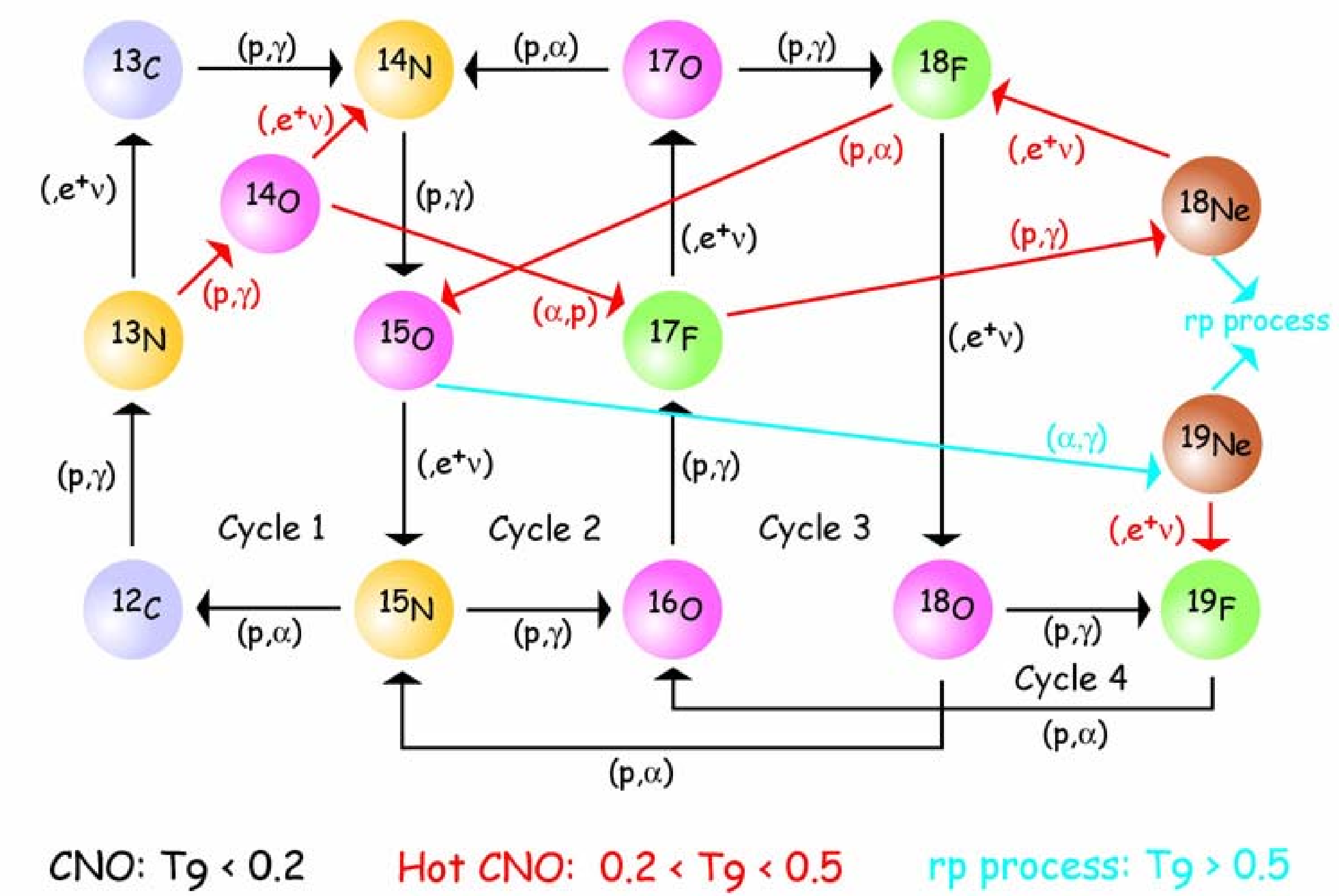
Hoyle state is underbound in NCSM with JISP16 by 8 MeV!

Lattice EFT produces α-cluster like structures for the Hoyle and g.s. state of ^{12}C

E. Epelbaum, et al., PRL 106, 192501 (2011)

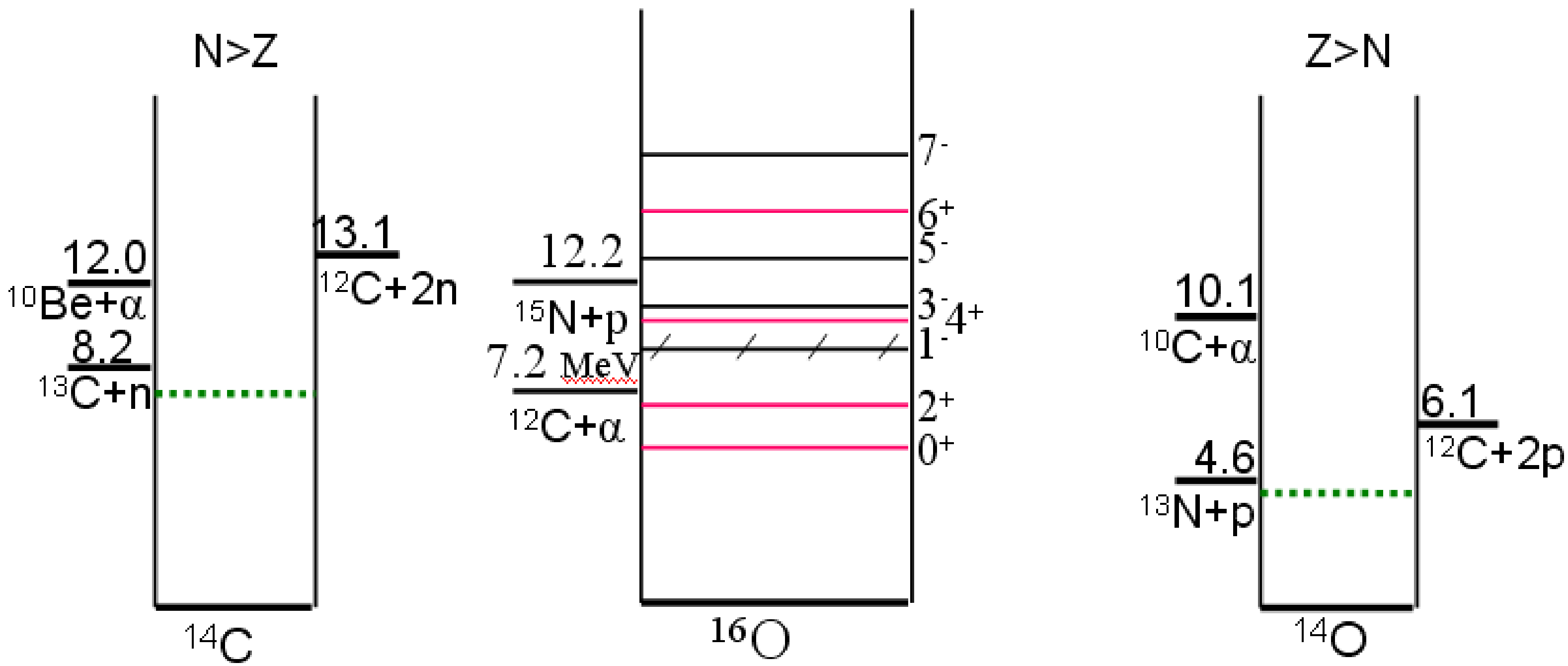
X-ray burst and novae

Break of CNO cycle



α-cluster structure of N$\neq$Z nuclei

Important: for astrophysics, due to breaking of CNO cycle through $^{14}O(\alpha,p)^{17}F$ reaction as an example;
for nuclear structure to provide for experimental observation of the relationship between the cluster and single particle approaches;
to use the ideas of the isospin conservation



1. THE SURFACE POTENTIAL MODEL

The simplest way to analyze the principal consequences of a surface potential model is to consider a potential that satisfies the boundary conditions $\Psi_\alpha(R) = 0$ and $\Psi_\alpha(R - \Delta R) = 0$, where R is the radius of the nucleus and ΔR is the thickness of the surface layer, i.e., a potential that confines the particle to a spherical surface layer of thickness ΔR.

The energy eigenvalues for the case $\Delta R \ll R$ can be easily found:

$$E = \frac{n^2\pi^2\hbar^2}{2\mu(\Delta R)^2} + \frac{\hbar^2 l(l+1)}{2\mu R^2}, \qquad (1)$$

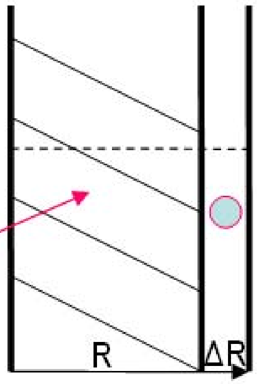
where μ is the reduced mass.

V. Z. Gol'dberg, V. P. Rudakov, and V. A. Timofeev

I. V. Kurchatov Atomic Energy Institute

(Submitted June 19, 1973)
Yad. Fiz. 19, 503–515 (March 1974)

What is inside ?

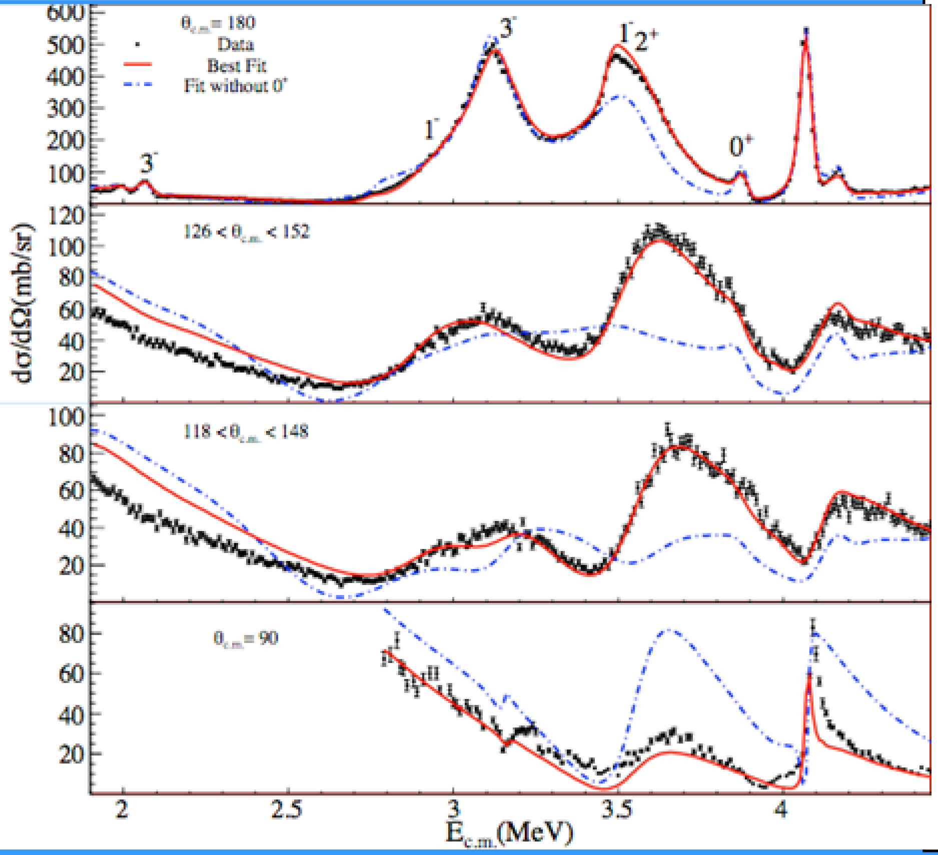


The number of nodes N for the radial wave functions are calculated by the harmonic-oscillator relations as
$2N + L = \Sigma(2n_i + l_i)$,
where L is the angular momentum of the cluster, while n_i and l_i the corresponding shell model numbers for nucleons

Resonances in the $\alpha+^{14}C$ interaction.

*E. Johnson, G.V.Rogachev, V.Z. Goldberg et al., Eur.Phys.J. A 42, 135 (**2009**)*

R-matrix fit of the $^{14}C(\alpha,\alpha)^{14}C$ excitation function



R-matrix fit of the $^{14}C(\alpha,n)$ excitation function.

Exp.data from Morgan et al., NP**A** 148 (1970)

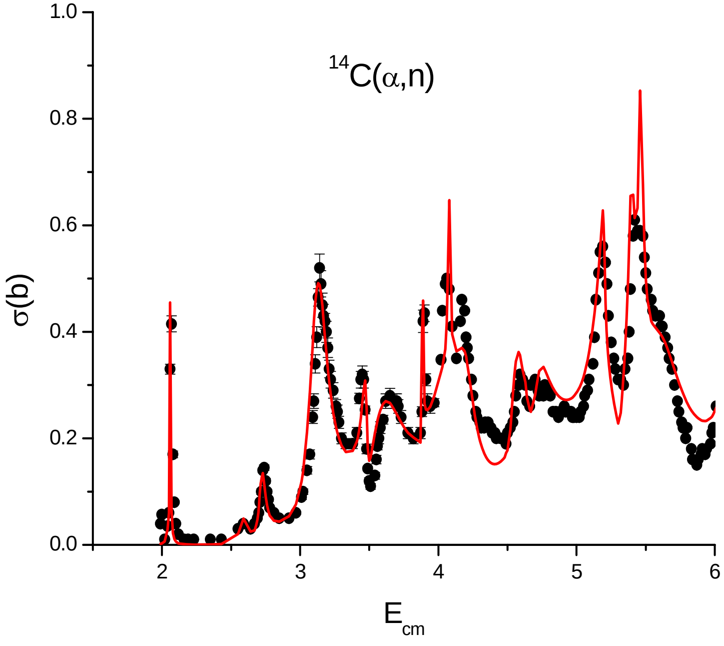


Table of States

0^+ states

E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
3.624	9.851	3209	3209	0			1.8536		

1^- states

E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
1.808	8.035	2	2	0	0.1021	0.1077	0.0199	0.0196	0.0186
2.904	9.131	166	152	14	1.6800	1.4891	0.1855	0.0905	0.1021
3.611	9.838	732	654	78			0.4578		
4.564	10.791	680	622	58			0.2913		
5.383	11.610	189	105	84			0.0386		
6.144	12.371	106	0.8	105.2			0.0002		
5.864	12.091	680	333	347			0.1087		
8.214	14.441	495	288	207			0.0675		
8.750	14.977	2611	1382	1229			0.2995		

2^+ states

E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
1.987	8.214	2	1.7	0.3	0.0585	0.0517	0.0270	0.0291	0.0329
2.732	8.959	69	5	64	0.3900	0.3380	0.0162	0.0128	0.0148
3.633	9.860	183	94	89	2.3050	1.4669	0.1011	0.0408	0.0641
4.168	10.395	180	43	137		3.9908	0.0321		0.0108
4.755	10.982	278	15	263			0.0086		
5.077	11.304	218	72	146			0.0358		
5.944	12.171	974	918	56			0.3543		
6.743	12.970	4892	4892	0			1.5922		
6.676	12.903	330	293	37			0.0965		
6.888	13.115	172	131	41			0.0476		
7.085	13.312	317	296	21			0.0908		
7.306	13.533	651	59	592			0.0144		
7.835	14.062	90	68	22			0.0185		

3^- states

E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
2.059	8.286	9	3	6	0.0135	0.0135	0.1775	0.2222	0.2222
2.586	8.813	58	0.3	57.7	0.0675	0.0683	0.0041	0.0044	0.0044
3.134	9.361	167	103	64	0.2185	0.2184	0.4812	0.4714	0.4717
3.470	9.697	138	15	123	0.3930	0.3837	0.0437	0.0382	0.0391
3.890	10.117	17	7	10	0.7440	0.7005	0.0128	0.0094	0.0100
4.169	10.396	65	18	47	1.1080	1.0010	0.0261	0.0162	0.0180
5.652	11.879	521	290	231		9.6527	0.1749		0.0300
6.128	12.355	85	2	83		11.3857	0.0012		0.0002
6.152	12.379	229	98	131		11.4454	0.0492		0.0086
6.412	12.639	730	650	80		11.7879	0.3019		0.0551
7.895	14.122	2533	2001	21567		11.2135	0.6620		0.1784
8.671	14.898	1076	627	449		12.5305	0.1828		0.0500

4^+ states

E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
4.073	10.300	27	17	10	0.2020	0.1435	0.0802	0.0842	0.1184
5.200	11.427	40	32	8	0.8696	0.5903	0.0506	0.0368	0.0542
6.322	12.549	8	7	1		1.6374	0.0058		0.0043
7.180	13.407	475	196	279		3.1697	0.1140		0.0618
7.666	13.893	52	10	42		4.5735	0.0052		0.0022
8.238	14.465	203	11	192		7.3832	0.0046		0.0015
8.254	14.481	287	144	143		7.4915	0.0616		0.0192
8.544	14.771	342	262	80			0.1050		

5^- States

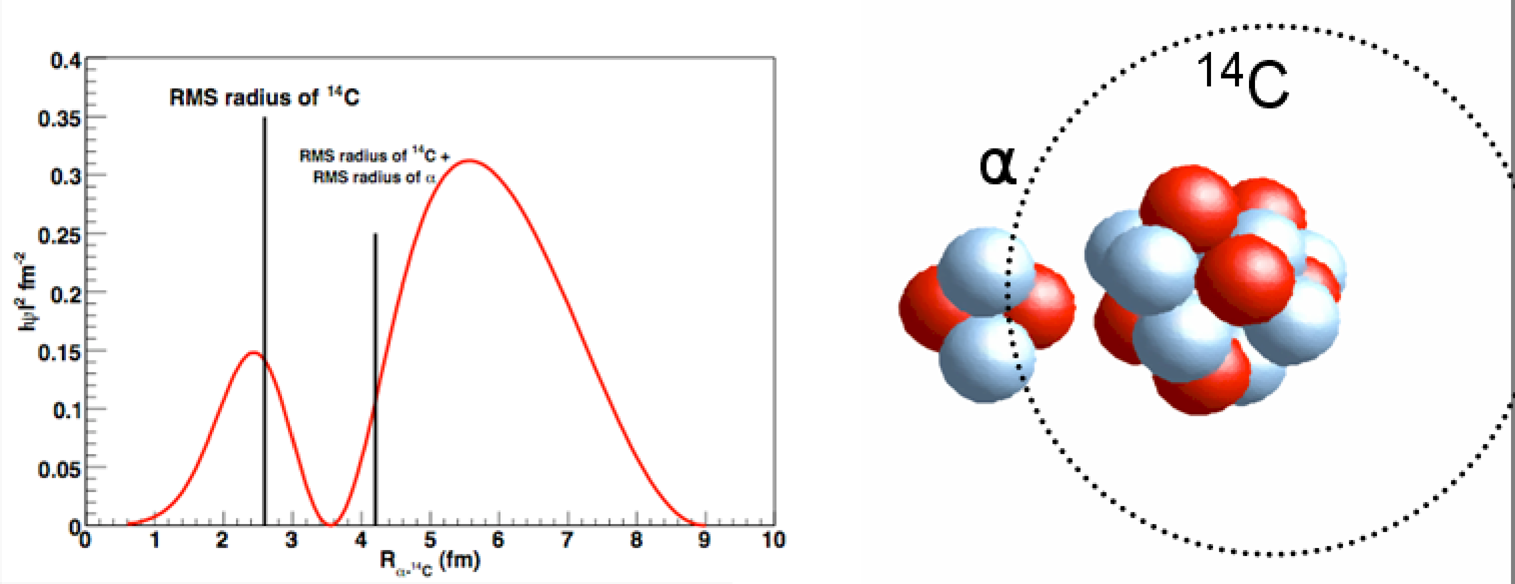
E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
5.409	11.636	41	30	11	0.196	0.1642	0.1274	0.1531	0.1827
6.115	12.342	37	25	12	0.438	0.3569	0.0575	0.0571	0.0700
6.716	12.943	67	25	42	0.799	0.6237	0.0386	0.0313	0.0401
6.877	13.104	128	95	33	0.927	0.7154	0.1346	0.1025	0.1328
7.897	14.124	611	293	318	2.485	1.5439	0.2504	0.1179	0.1898
7.573	13.800	31	2	29	1.768	1.2291	0.0023	0.0011	0.0016
8.497	14.724	251	202	49		2.2940	0.1375		0.0881
8.543	14.770	128	94	34		2.3598	0.0634		0.0398

6^+ states

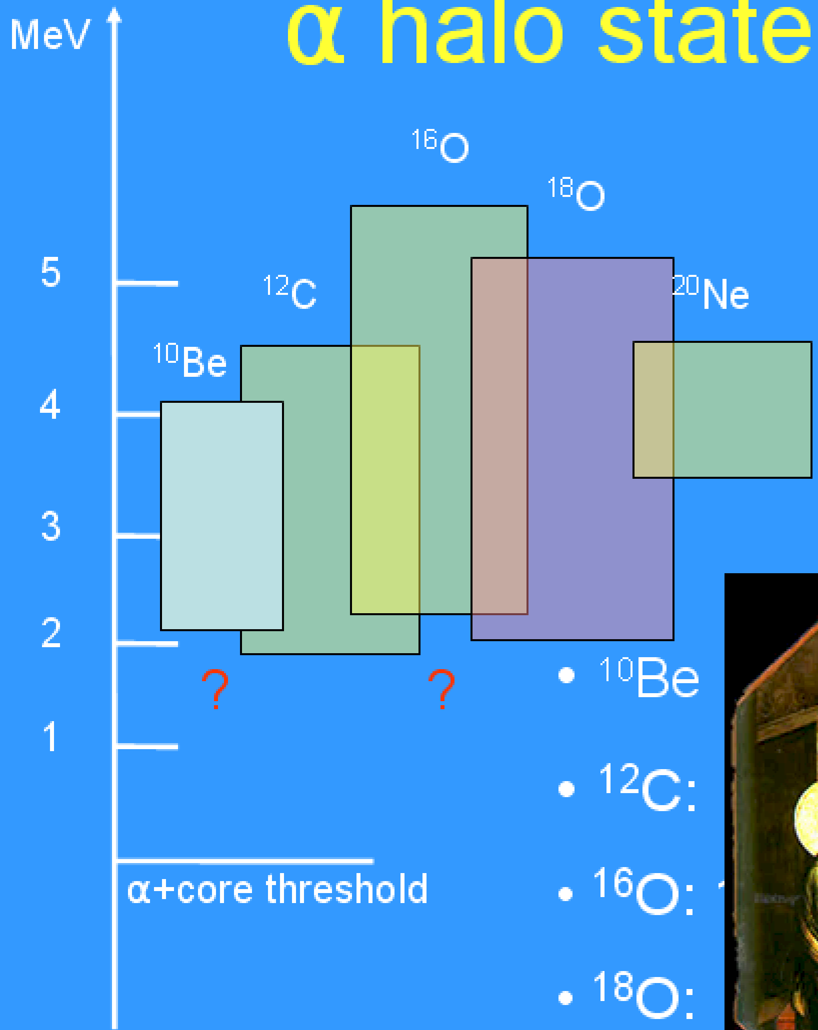
E[MeV]	E_{exc}[MeV]	Γ_{tot}[keV]	Γ_α[keV]	Γ_n[keV]	Robson's Pot $\Gamma_{\alpha S.P.}$[keV]	Volya's Pot $\Gamma_{\alpha S.P.}$[keV]	Rmatrix θ_α^2	Robson θ_α^2	Volya θ_α^2
5.475	11.702	19	10	9	0.0233	0.0232	0.2060	0.4292	
6.369	12.596	81	54	27	0.0765	0.0294	0.4019	0.7059	1.8395

α halo state in ^{18}O

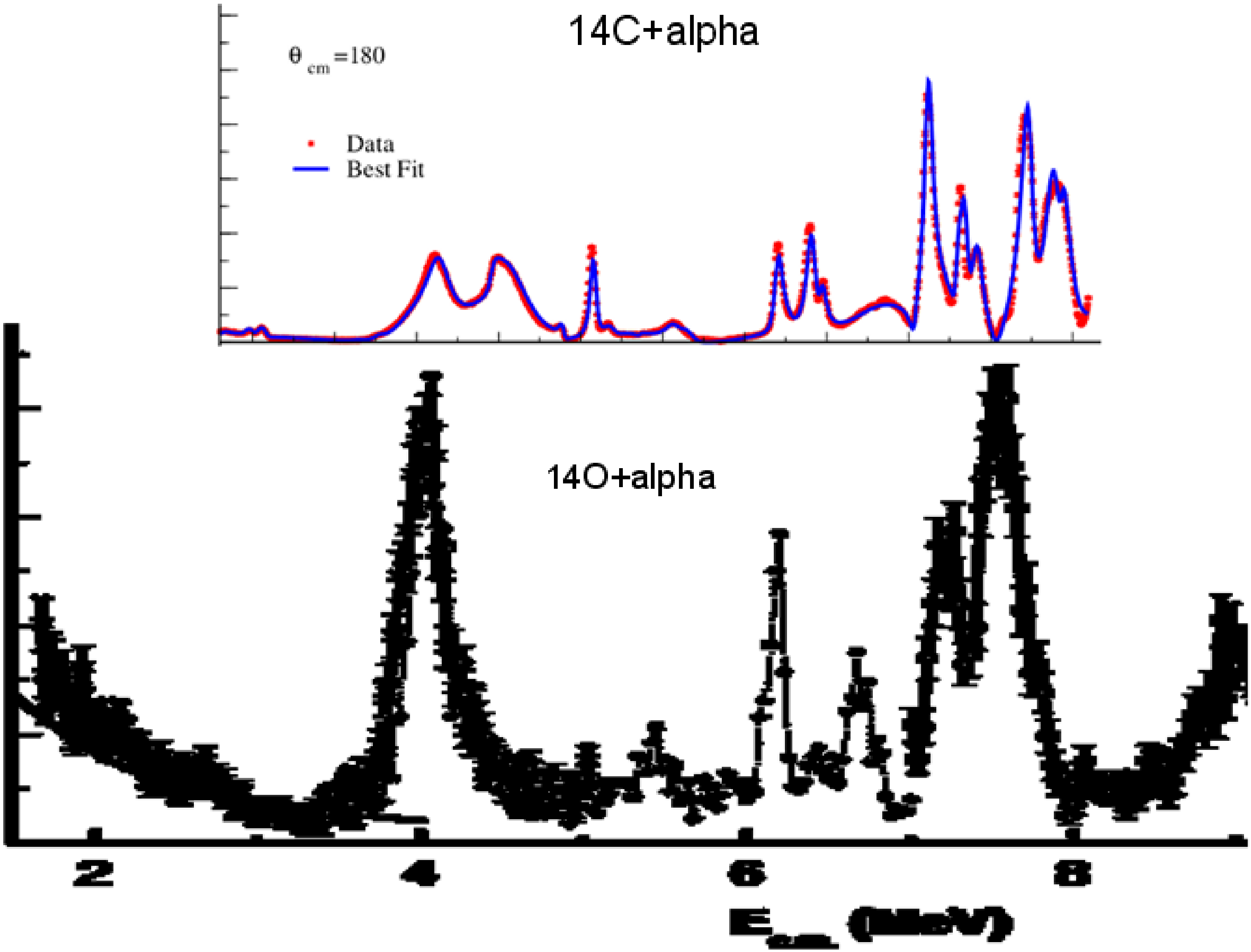
0^+ at 3.8+/-0.5 MeV (~10.0 MeV ^{18}O excitation energy) with width of ~3-5 MeV is necessary to fit the $\alpha+^{14}$C data.
This width corresponds to purely α particle state.



α halo states



- ^{10}Be
- ^{12}C:
- ^{16}O: 1
- ^{18}O:
- ^{20}Ne:



The spectra do differ

A=10 isobaric triplet

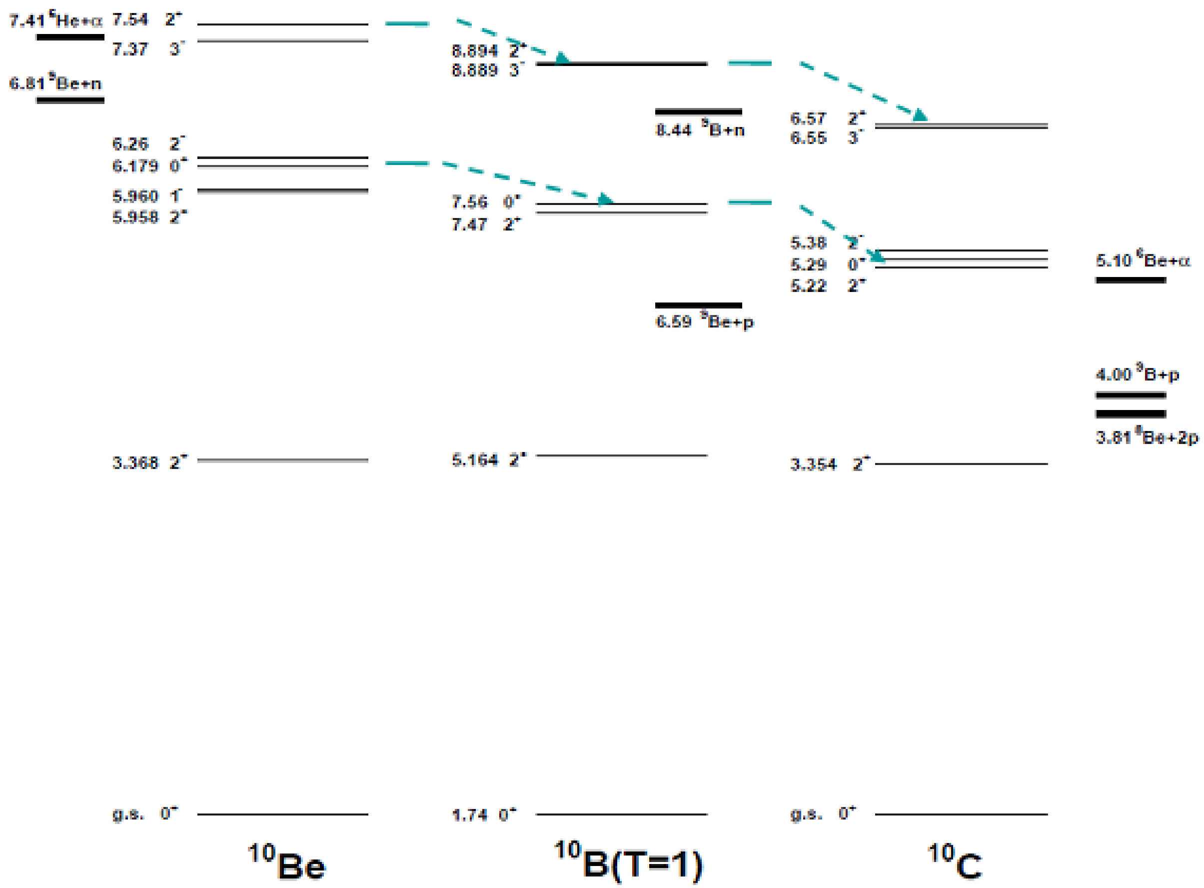


FIG. 1. Levels diagram for the A=10 T=1 isobaric multiplet.

SUMMARY

1. Problems of the nuclear astrophysics, development of the ab initio calculations pushed up the interest to the structure of unstable light nuclei.
2. Rare isotope beam-hydrogen resonance scattering provides for the detailed data. It is important that the experiments are feasible at low intensities of the rare isotope beams
3. Rare isotope beam-helium, $A(N \neq Z)+\alpha$, resonance studies are in the very beginning. Due to the reasons [1] and the interest to specific nuclear structure of the α-cluster states, I expect these studies will be very popular in the nearest future.
4. I also expect a growing interest to the studies of analog states of the very neutron rich nuclei using resonance scattering of neutron rich nuclei on hydrogen. Sorry, I could not consider this problem in the present talk

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[V.Z.G and G.V. Rogachev
Phys. Rev. C 86, 044314 (2012)]

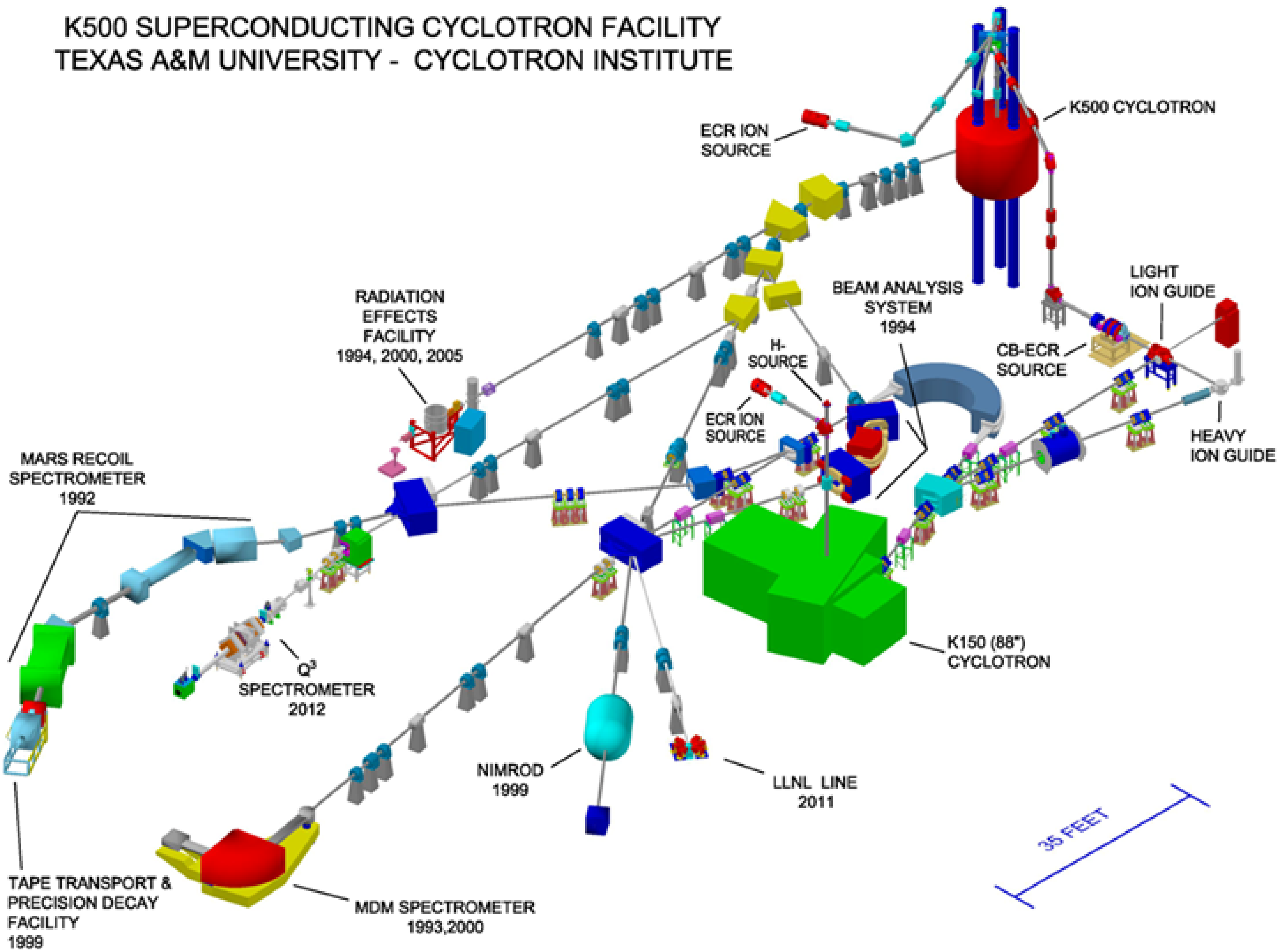
Alpha-Cluster States in A=10

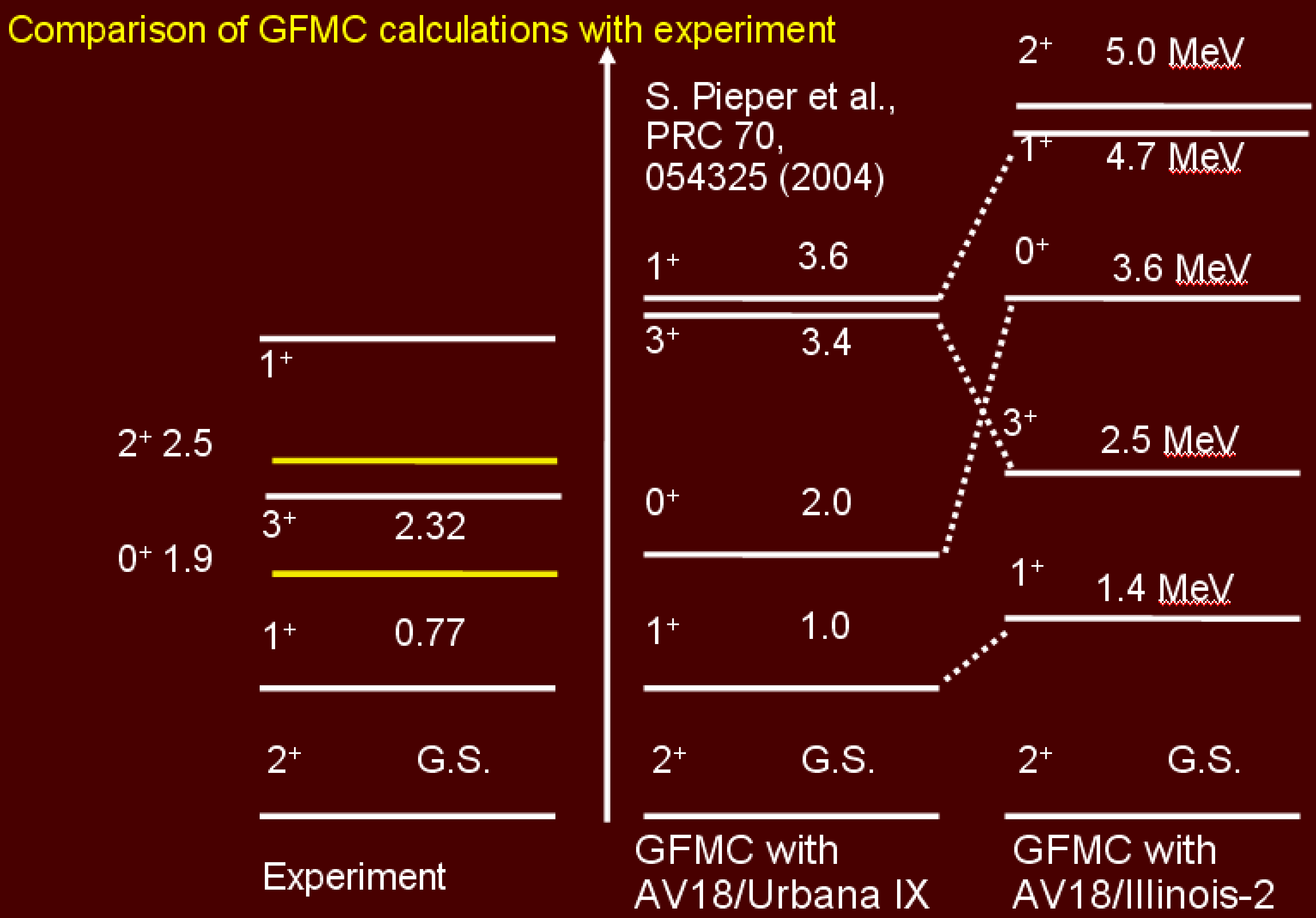
1. Potential well model predictions and the levels in ^{10}Be,B (T=1).

2. Resonance scattering to study of T=1 levels in ^{10}B

3. Analisys of available ^{10}Be,B,C data (^{10}C – see R. J. Charity, T. D. Wiser, K. Mercurio et al., Phys. Rev. C 80, 024306 (2009)) using shell model (A. S. Volya, continuum shell model code cosmo, http://www.volya.net.) and potential well model for cluster calculations

4. ^{6}He+α resonance scattering

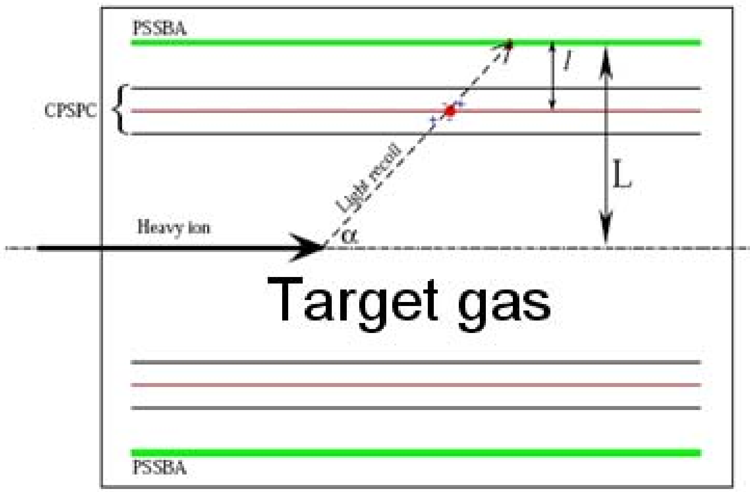

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE
ECR ION SOURCE
K500 CYCLOTRON
RADIATION EFFECTS FACILITY 1994, 2000, 2005
BEAM ANALYSIS SYSTEM 1994
LIGHT ION GUIDE
CB-ECR SOURCE
H- SOURCE
ECR ION SOURCE
HEAVY ION GUIDE
MARS RECOIL SPECTROMETER 1992
K150 (88") CYCLOTRON
Q3 SPECTROMETER 2012
NIMROD 1999
LLNL LINE 2011
35 FEET
TAPE TRANSPORT & PRECISION DECAY FACILITY 1999
MDM SPECTROMETER 1993,2000

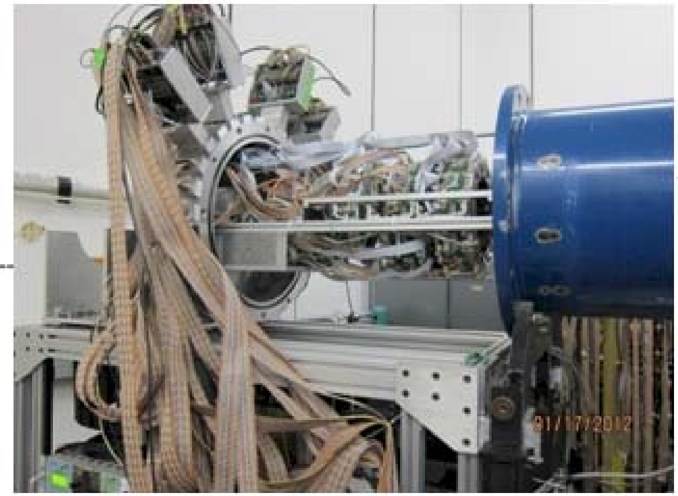


Comparison of GFMC calculations with experiment
S. Pieper et al.,
PRC 70,
054325 (2004)
1+
2+ 2.5
3+ 2.32
0+ 1.9
1+ 0.77
2+ G.S.
Experiment
1+ 3.6
3+ 3.4
0+ 2.0
1+ 1.0
2+ G.S.
GFMC with
AV18/Urbana IX
2+ 5.0 MeV
1+ 4.7 MeV
0+ 3.6 MeV
3+ 2.5 MeV
1+ 1.4 MeV
2+ G.S.
GFMC with
AV18/Illinois-2

ANASEN

Array for Nuclear Astrophysics and Structure with Exotic Nuclei





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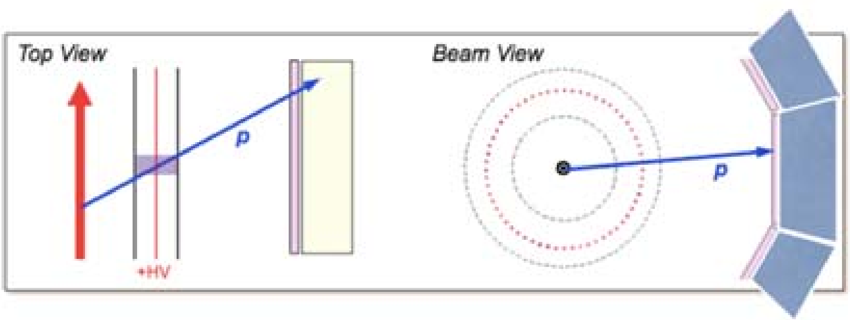
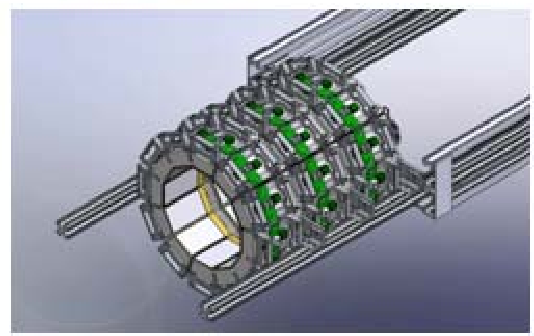
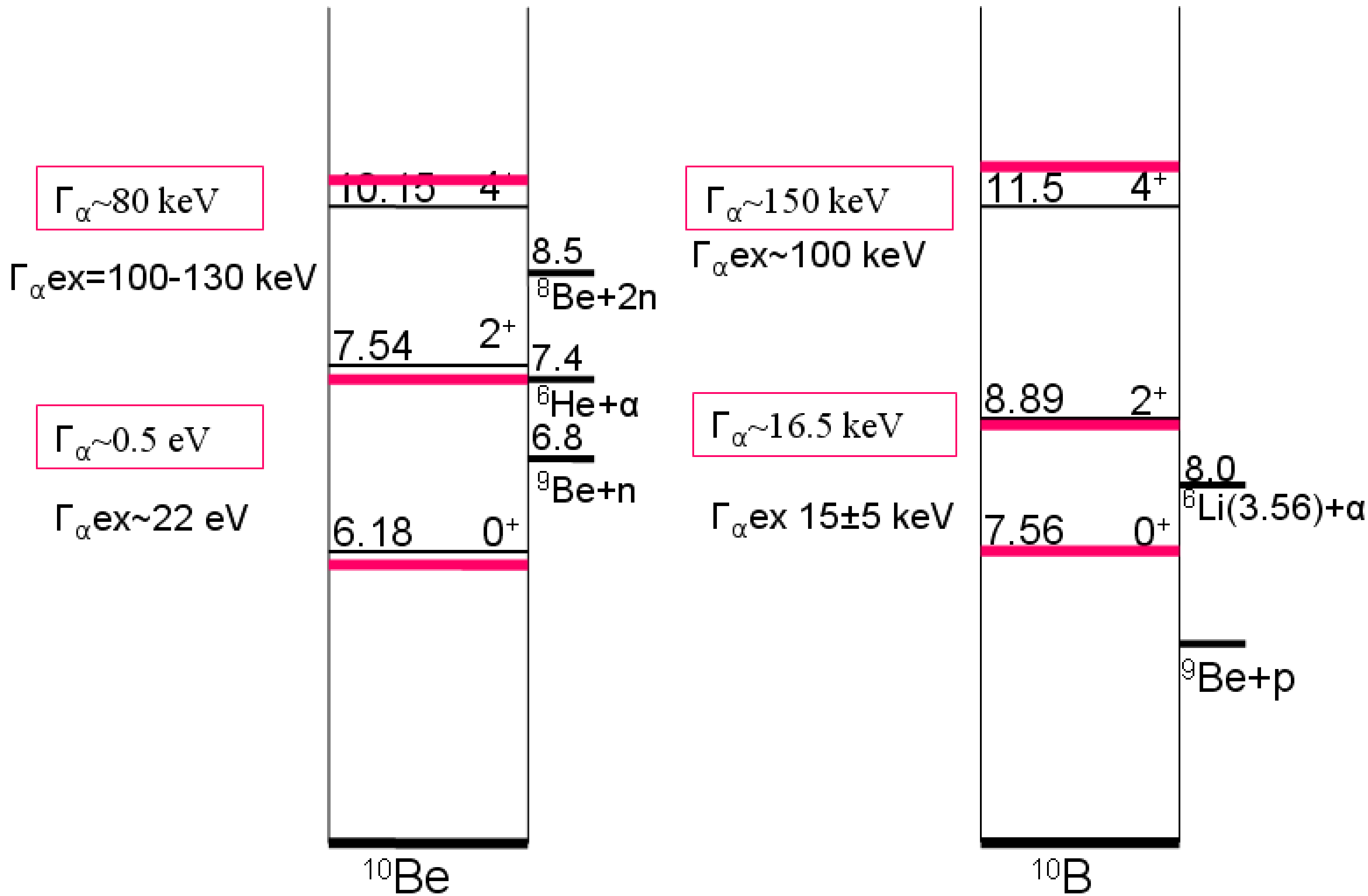


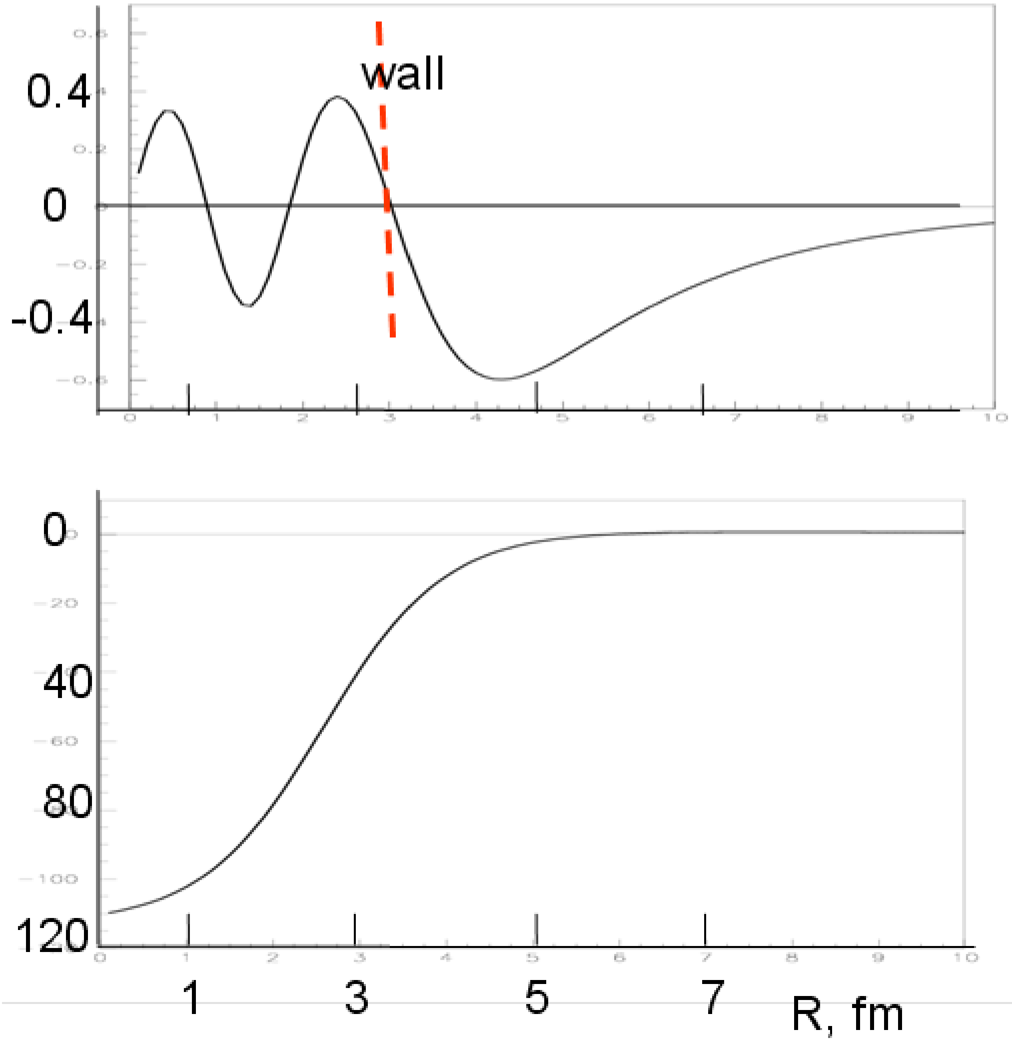


Potential parameters

R=2.58 fm; a=0.7 fm; V_0=-116.8 MeV



^{10}Be (α+^{6}He)



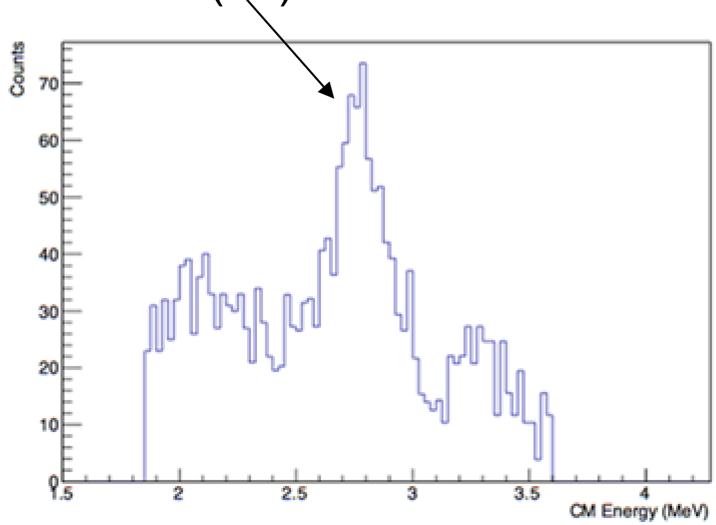
α+^{6}He wave function for the 0^{+} 6.2 Mev level in a potential well with forbidden states

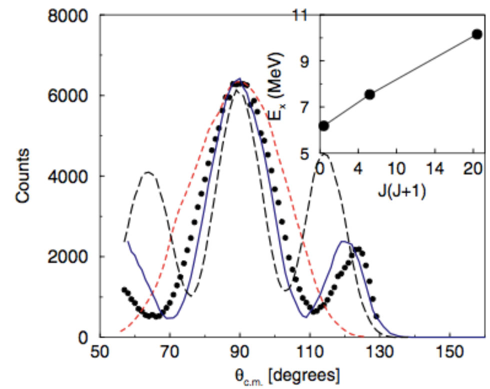
$$\Sigma 2n_i + l_i = 2N + L$$

Potential parameters
R=2.58 fm; a=0.7 fm;
V_0=-116.8 MeV

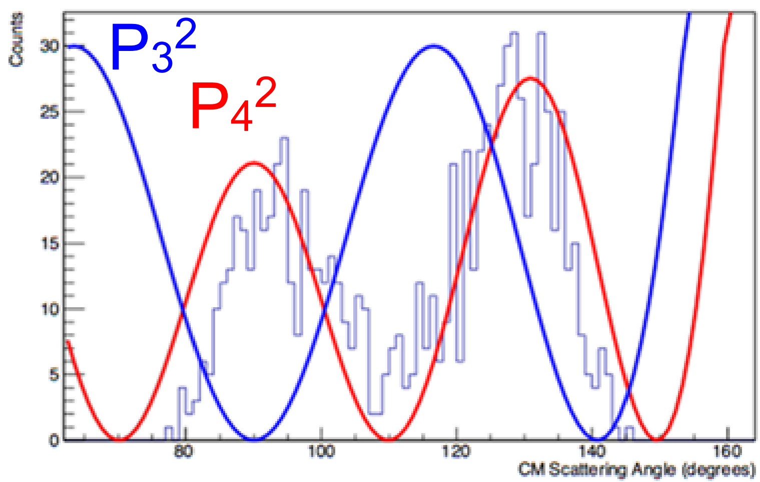
$^{6}He+\alpha$ experiment

The peak is at 10.16(2) MeV of ^{10}Be excitation energy; Γ_{tot}=270(30) keV





M. Freer, et al., PRL 96 (2006)



Angular distribution if gated around 2.75+/-0.1 MeV

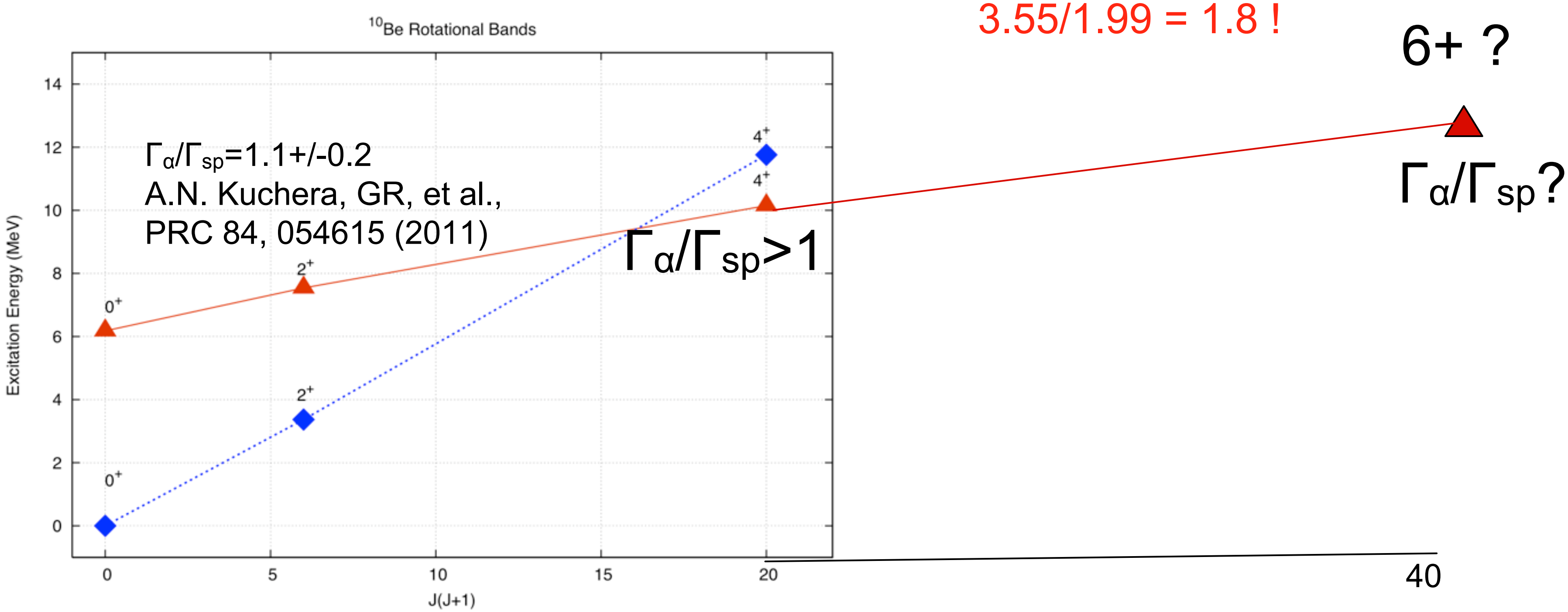
Green's function Monte
Carlo (GFMC) algorithm
Nuclear structure of 7Be, 8B, and 7,8Li is studied within the *ab initio* no-core shell model (NCSM).
ab initio lattice
results PRL109,252(2012);
no-core shell model PRL107,072501(2011)
Fermionic molecular
dynamics Phys. Rev. Lett. 105, 022501(2010)
Forces two-body AV18, "two-body" +3-GISP16

Moment of inertia ratio for the g.s. band and band based on 0+ at 6.2 MeV:

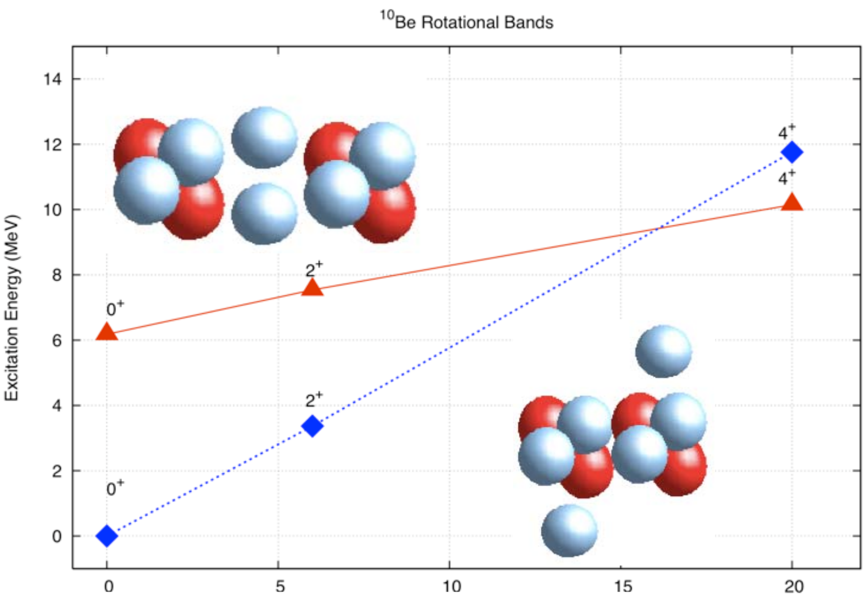
$I_{6.2}/ I_{gs} \approx 3.2$ → $R_{6.2}/R_{gs} \approx 1.8$

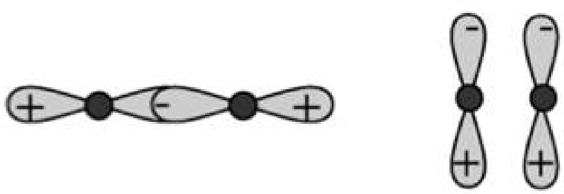
A. Dote, et al., PRC 56, 1844 (1997)

AMD+HF approach prediction:
interalpha distance
gs 0+ 1.99 fm
6.2 MeV 0+ 3.55 fm
3.55/1.99 = 1.8 !



Clustering in ^{10}Be

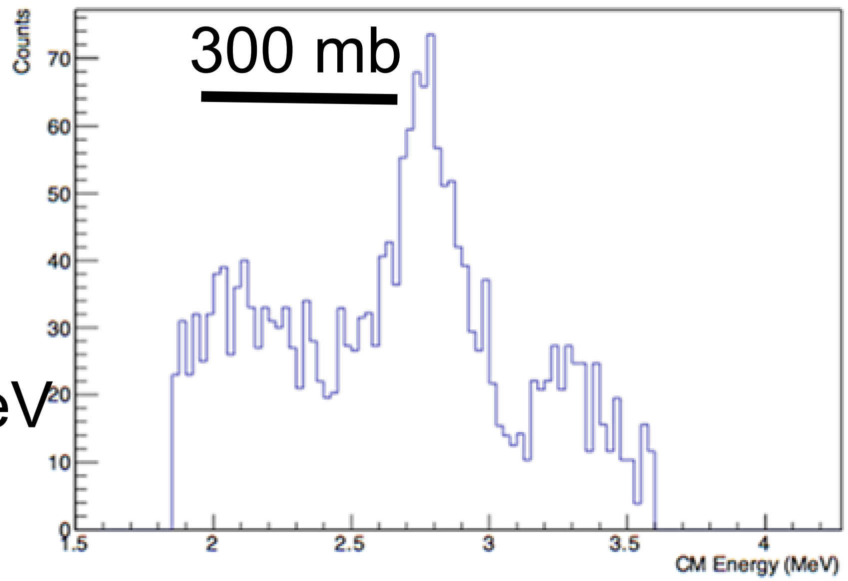




- ➢ Rotational band with high moment of inertia built on 0^+ at 6.18 MeV
- ➢ 10.15 MeV state reported to be extremely clustered [1]
- ➢ Believed to be associated with α-2n-α molecular rotational band.
- ➢ Disagreement in spin-parity assignment for 10.15 MeV
  - 4^+ in [1,2]
  - 3^- in [3]

[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

^{6}He +α elastic scattering



Maximum cross section for pure α-cluster 4^+ at 2.75 MeV is ~400 mb.

α-partial width >150 keV is needed to explain the observed cross section!

Maximum α-partial width for pure α-^{6}He 4^+ state at 2.75 MeV is ~100 keV

Model levels in mirror nuclei

The Coulomb shift energies could be a valuable source of information

V.Z. Goldberg et al., Phys. Rev. **C 69**, 031302(R) (2004)