Mystery of ^{9}He and Very Neutron Rich Nuclei ^{8}He, ^{10}He, and ^{7}H

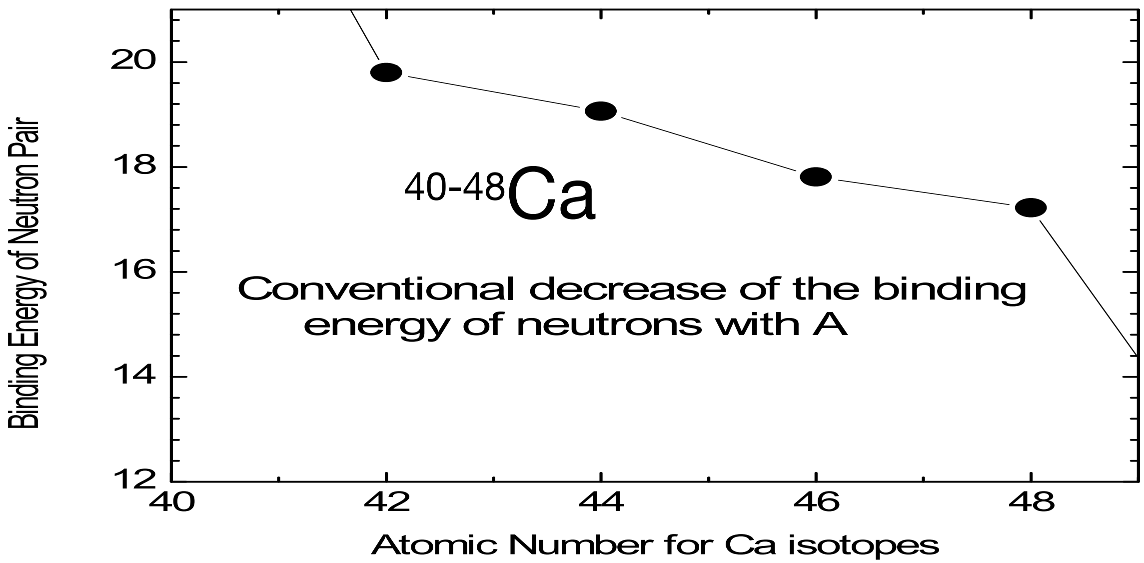
V.Z. Goldberg

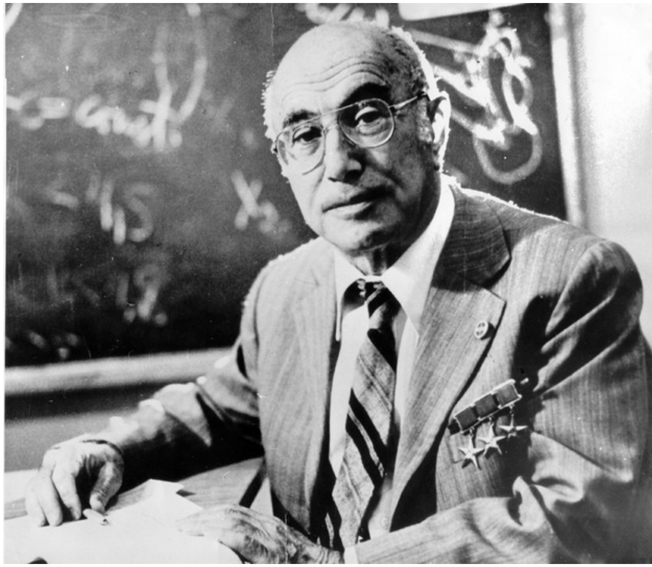
Texas A&M University

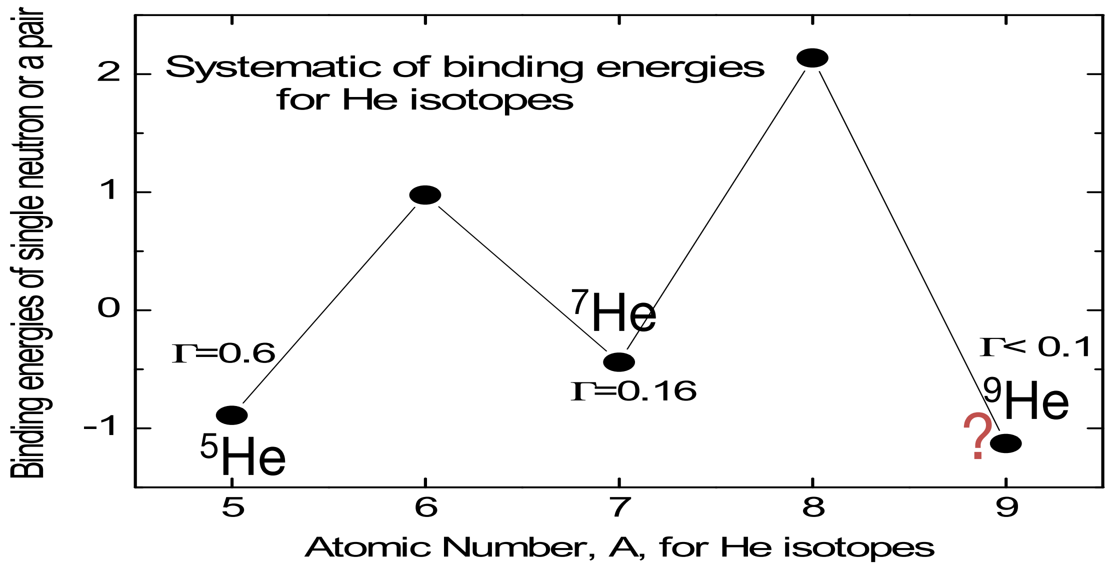
LXV International Conference on Nuclear Physics
Saint Petersburg June 30 2015

Systematics of binding energies of single/pair of neutrons in neutron rich nuclei

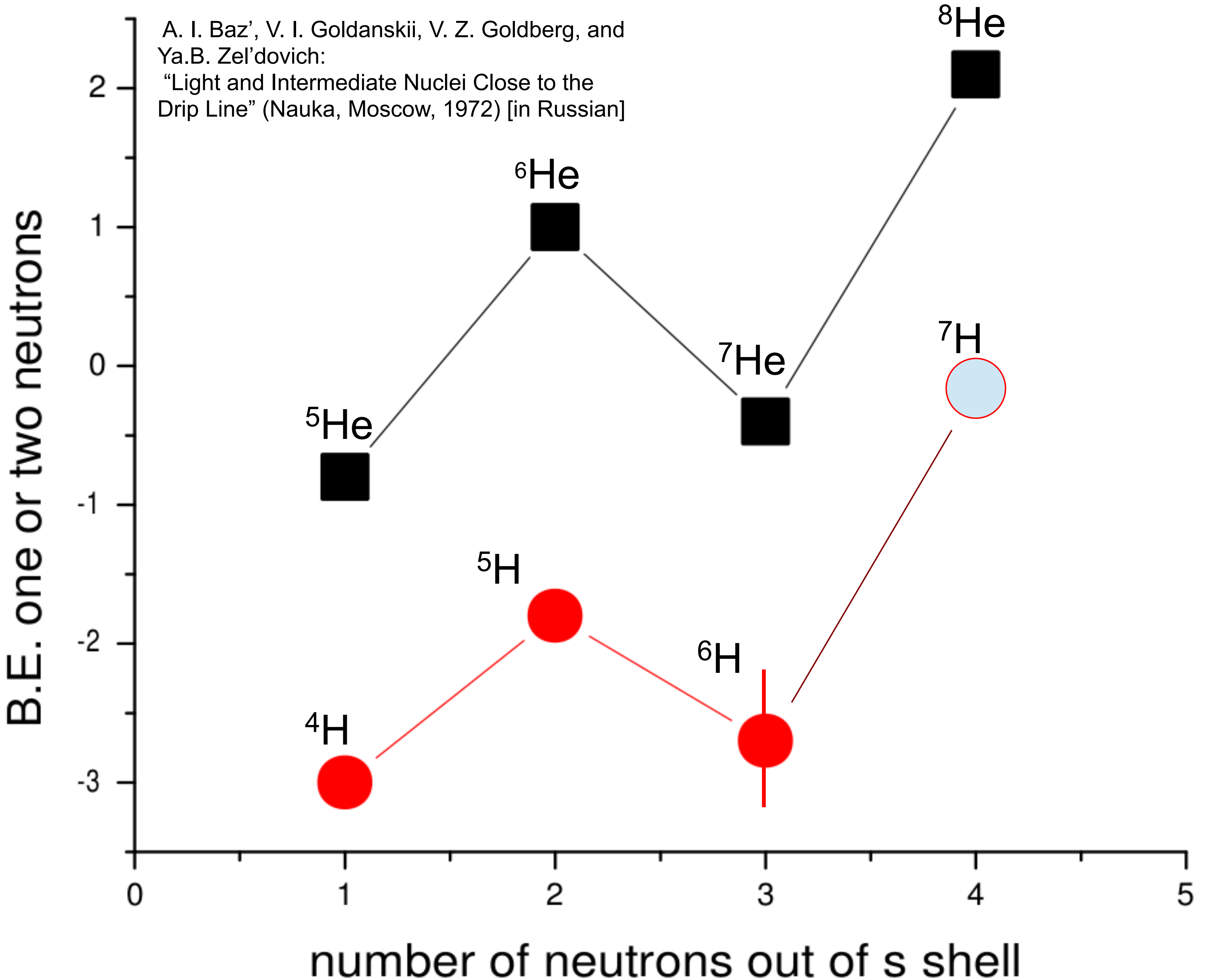
Я. Б. Зельдович ЖЭТФ, 1960, т. 38 с. 1123





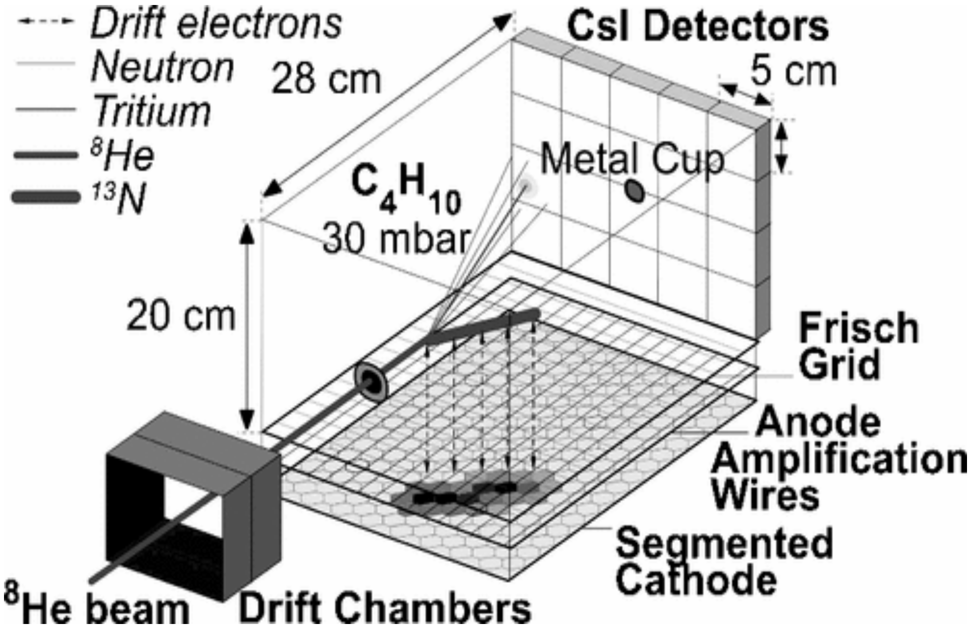


Neutron Stability of of He and H Isotopes

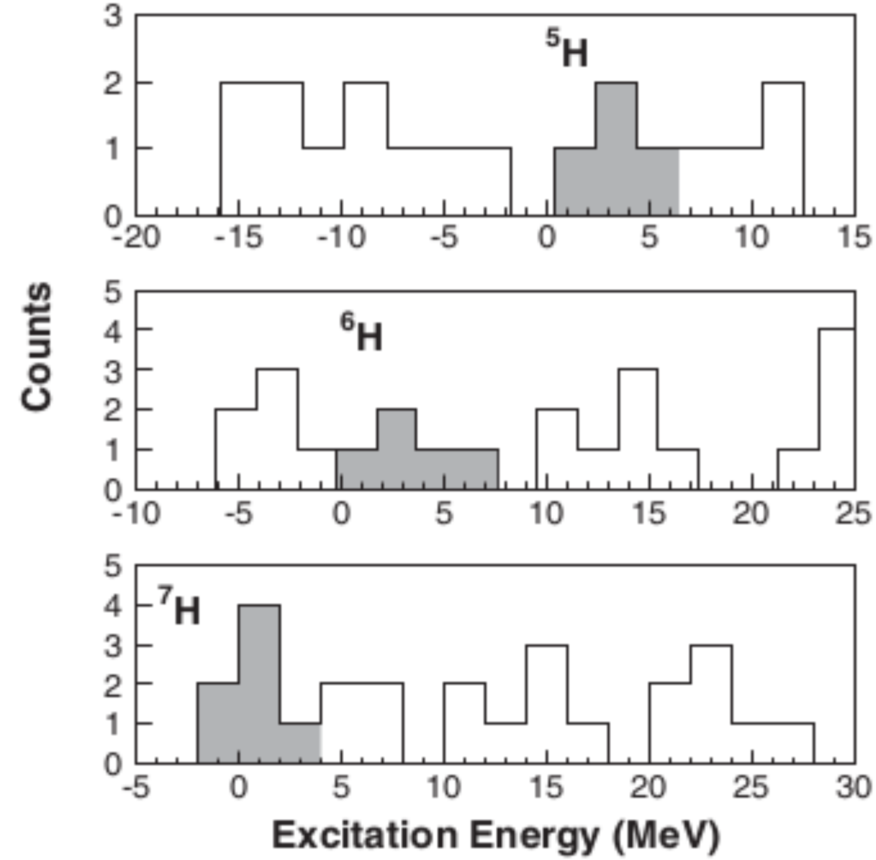


$^{8}He+^{12}C \rightarrow ^{7}H+^{13}N$

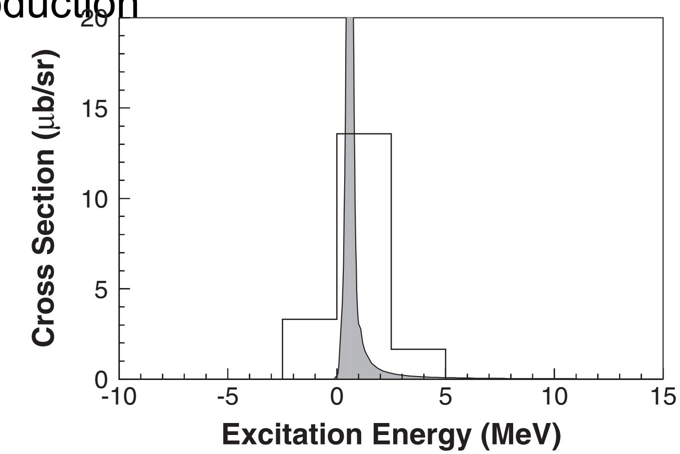
M. Caamano et al., PRL99, 062502 (2007)



Experimental setup.
Drift chambers in front of MAYA monitor the beam particles.
The reactions occur in the volume filled with C_4H_{10} gas.
A matrix of CsI detectors is placed at the back side for detecting light particles. A small metal cup is used to stop the beam.



Excitation energy distributions under the assumptions of the ^{5}H, ^{6}H, and ^{7}H production



The fitted parameters result in a width of ~0.09 MeV and a resonance energy ~0.57 MeV above the threshold of the 3H +4n system.

$^{8}He+^{2}H \rightarrow ^{7}H+^{3}He$

E. Yu. Nikolskii et al., Phys. Rev. C81,064606(2010)

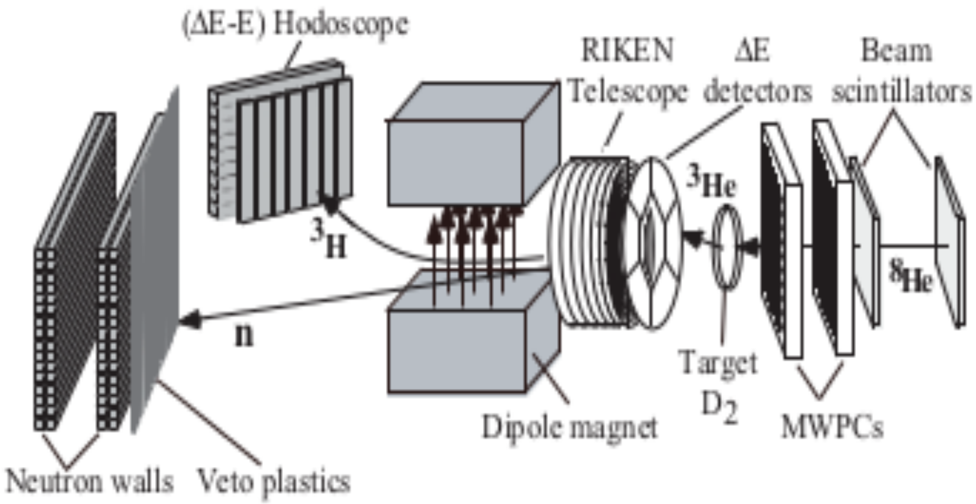
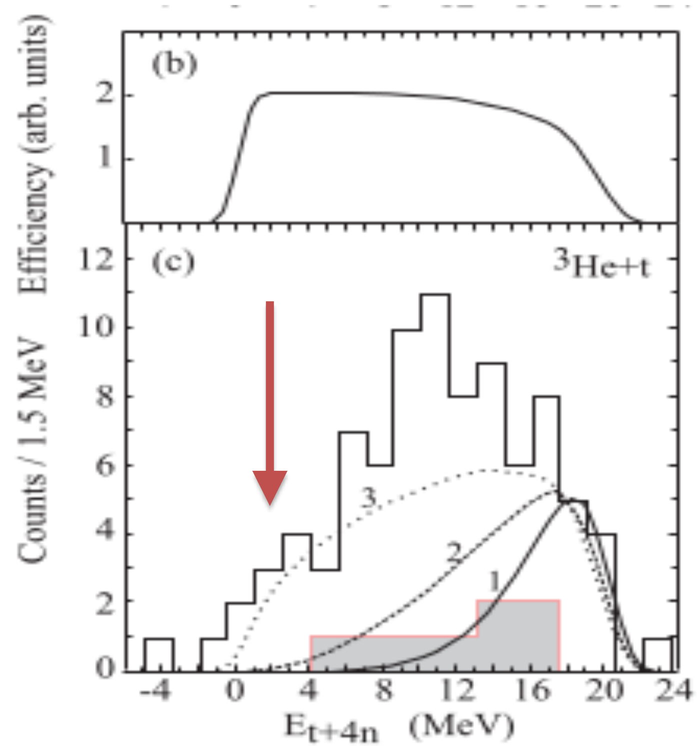


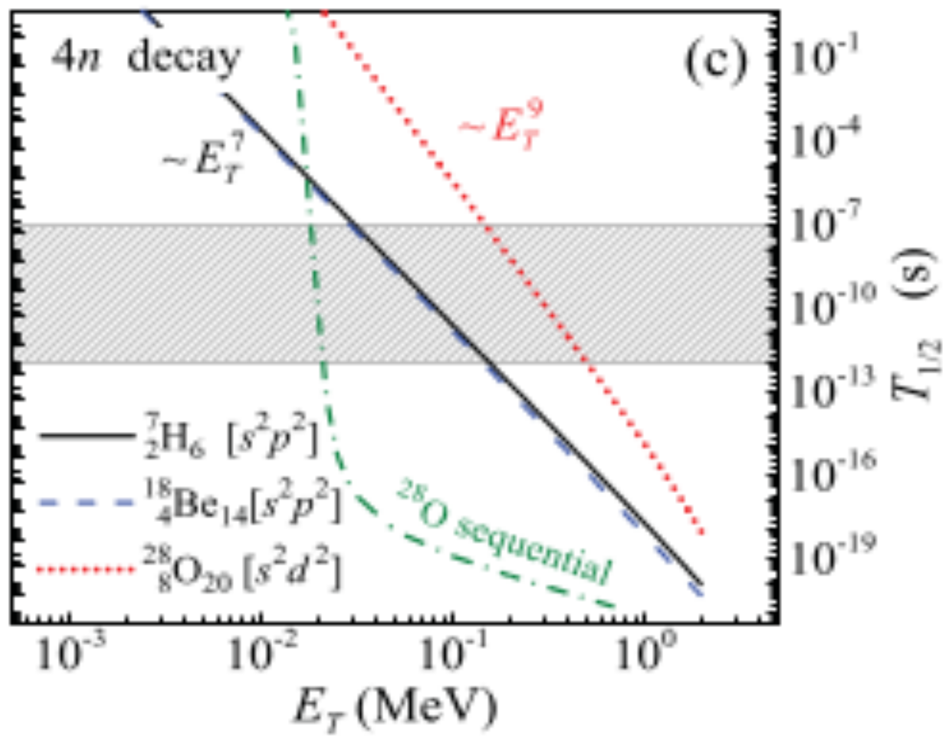
FIG. 1. Experimental setup.



Missing-mass spectra of ^{7}H from the reaction $^{2}H(^{8}He,^{3}He)$: (b) detection efficiency in arbitrary units, and (c) in coincidence with tritons.

"...for the $^{2}H(^{8}He,^{3}He)^{7}H$ reaction, one may expect a cross section of ~2.5 mb/sr, which is almost 2 orders of magnitude larger than the cross section determined for this reaction in the work of M. Caamano et al. ….The results... are in conflict with each other."

L. Grigorenko et al., Phys.Rev. C 84, 021303 (2011)



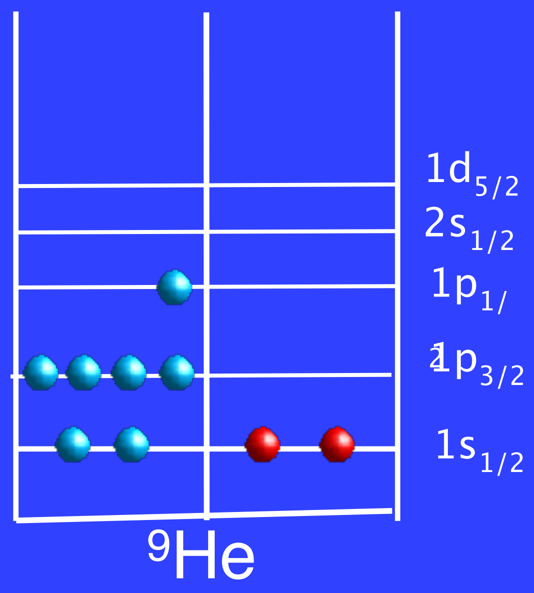
Estimated widths for true 4n emission calculated for different orbital configurations; the low-energy behavior of the widths has an asymptotic dependence ~ E_t^{α}

^{7}H Summary

The ^{7}H problem is still open.
We do not have reliable data on the properties of this exotic nuclei.
Integrating the available data one may expect of a few MeV ^{7}H neutron decay instability.

Mystery! Beyond Neutron Drip line!: ^{9}He ^{10}He, and ^{7}H

		^{7}Li +2.5	^{8}Li +2.0	^{9}Li +4.1	^{10}Li -0.02	^{11}Li +0.25
	^{5}He -0.80	**^{6}He +1.0**	^{7}He −0.44	^{8}He +2.1	^{9}He -0.1**?**	^{10}He -1.1**?**
^{3}H	^{4}H -3.2	^{5}H -1.8	^{6}H -3.1	^{7}H -?		



The width of the ^{9}He ground state is 100±60 keV, [H.G. Bohlen et al., Prog. Part. Nucl. Phys., 42 (1999) 17].
While this state is expected to be a single particle one (SM, NCSM and GFMC, ab initio K.M.Nollett Phys.Rev. C 86, 044330 (2012)).

So $\Gamma_{1/2}$- should be ~ 1.0 MeV

The disagreement means that the ground state of ^{9}He has very unusual structure which we do not understand.

Eureka!!!

Does ^{9}He continue the trend for proton deficient N=7 isotones?

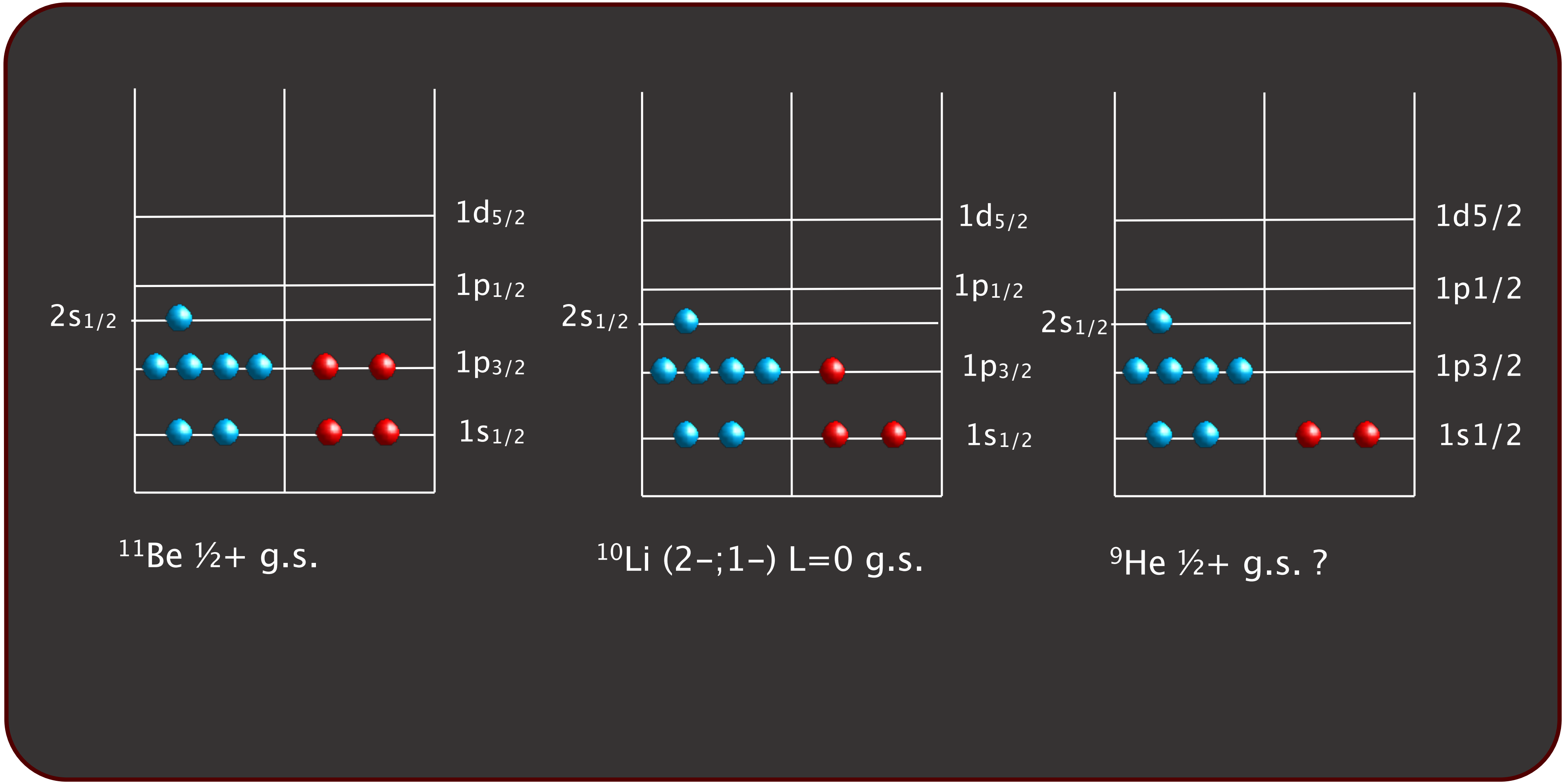


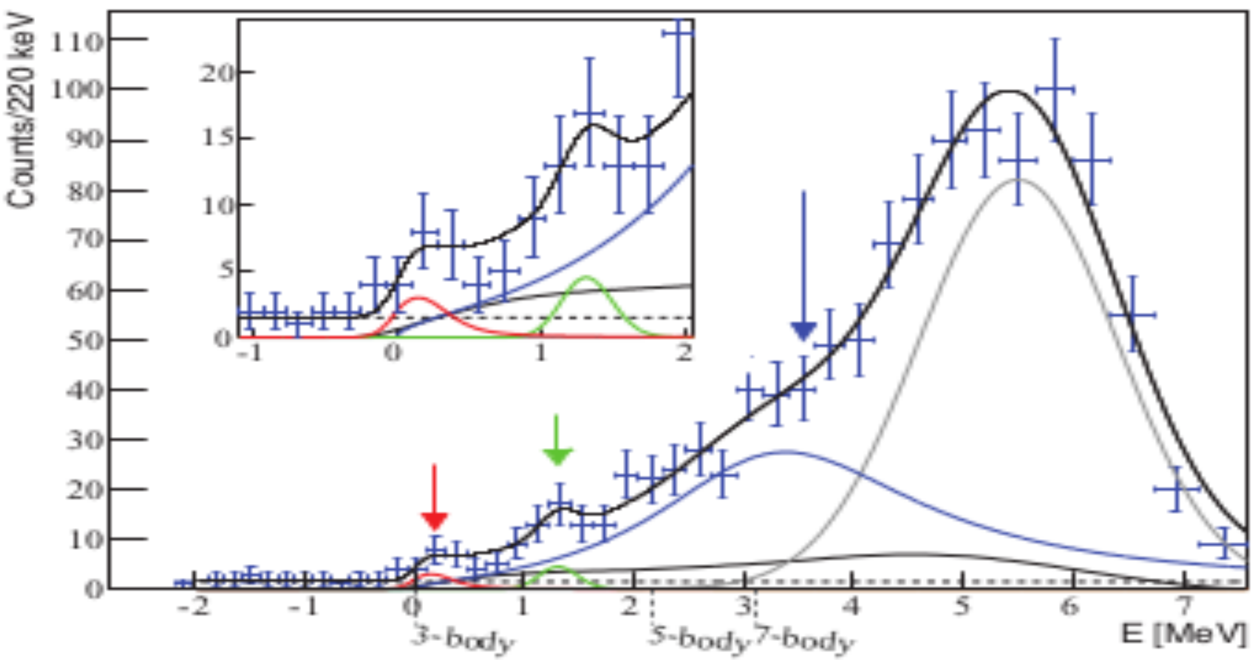
TABLE I. Energies (relative to the ^{8}He + n threshold) and widths (both in MeV) of resonances in ^{9}He from the reactions indicated.

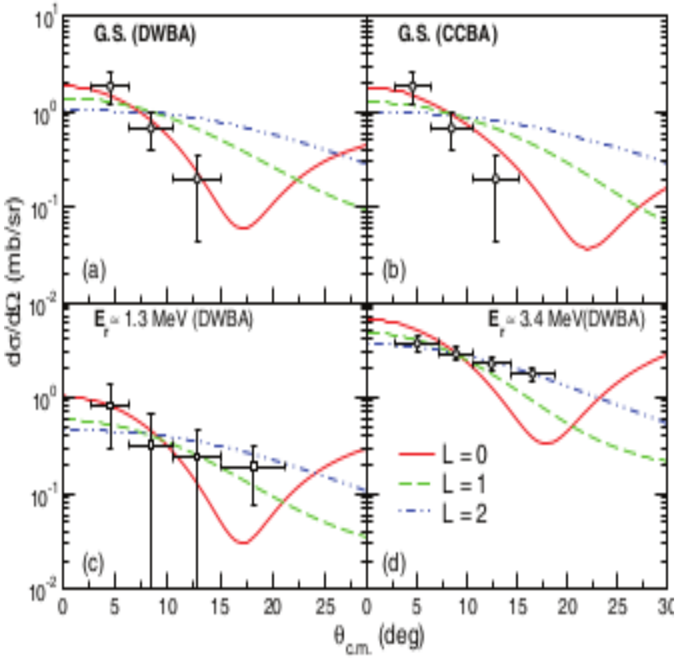
Label	Reaction	E_n	Width	J^π	Reference
1	^{9}Be(π^-,π^+)	1.13(10)	0.42(10)	$1/2^-$	[4]
		2.33(10)	0.42(10)	$1/2^+$	
		4.93(10)	0.50(10)	$5/2^+$ or $3/2^-$	1987
2	^{9}Be(^{13}C, ^{13}O) and	1.13	~0.30	$1/2^-$	[5]
	^{9}Be(^{14}C, ^{14}O)	2.28	~0.85	$1/2^+$ or $3/2^-$	
		4.93			1995
3	^{9}Be(^{14}C, ^{14}O)	1.27	0.10(6)	$1/2^-$	[6]
		2.37(10)	0.7(2)	$(3/2^-)$	
		4.30(10)	Narrow	$(5/2^+)$	1999
		5.25(10)	Narrow		
4	$2p$ knockout from ^{11}Be	(<0.2)		$1/2^+$	[7]
5	C(^{11}Be, ^{8}He + n)	<0.2		$1/2^+$	[8]
	C(^{14}B, ^{8}He + n)	~0		$1/2^+$	2001
		~1.3	~1		2011
6	^{2}H(^{11}Li, ^{8}He + n)	(~0)	Maybe not a true state		[9]
		1.33(8)	0.10 fixed	$1/2^-$	
		2.42(10)	0.70 fixed	$3/2^-$	2010
7	^{2}H(^{8}He, p)	~0		$(1/2^+)$	[10]
		~1.3		$(1/2^-)$	2007
		~2.3			
8	^{2}H(^{8}He, p)	~0		$1/2^+$	[11]
		2.0(2)	~2	$1/2^-$	2007
		>4.2	>0.5	$5/2^+$	
9	^{2}H(^{8}He, p)	0.180(85)	0.18(16)	$1/2^+$	[12]
		1.235(115)	0.13(17)	$(1/2^-)$	2013
		3.42(78)	2.90(39)	$5/2^+$ or $3/2^+$	

T. AL KALANEE et al. PHYS. REV. C 88, 034301 (2013)

D(^{8}He,p)^{9}He

"Two peaks can clearly be seen: one approximately 200 keV above threshold which we identified as g.s. and another around 1.5 MeV."



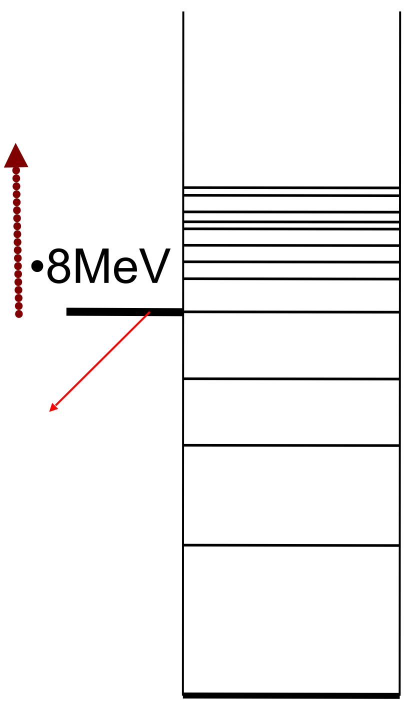


Experimental missing mass spectrum for the (p,^{8}He)p reaction which is described with three states:ground state (red), first excited (green), and second excited (blue) states. The dotted line indicates the physical background due to reactions of the beam with the plastic scintillator.

Angular distributions for the ground State (a) and the two first excited states of ^{9}He and (d)] compared to *L = 0, 1, 2* DWBA calculations.

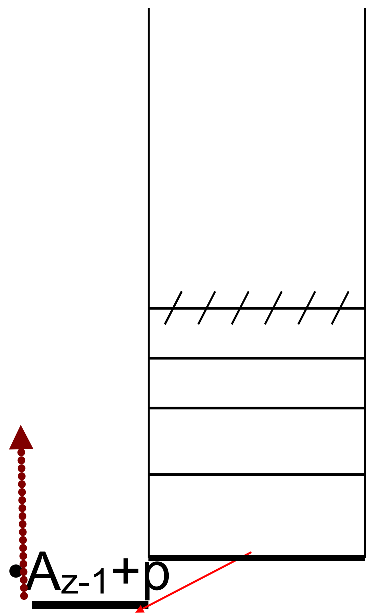
Resonances in exotic nuclei

- Conventional nucleus



- Density of levels is high. Practically it is not possible to use theoretical predictions

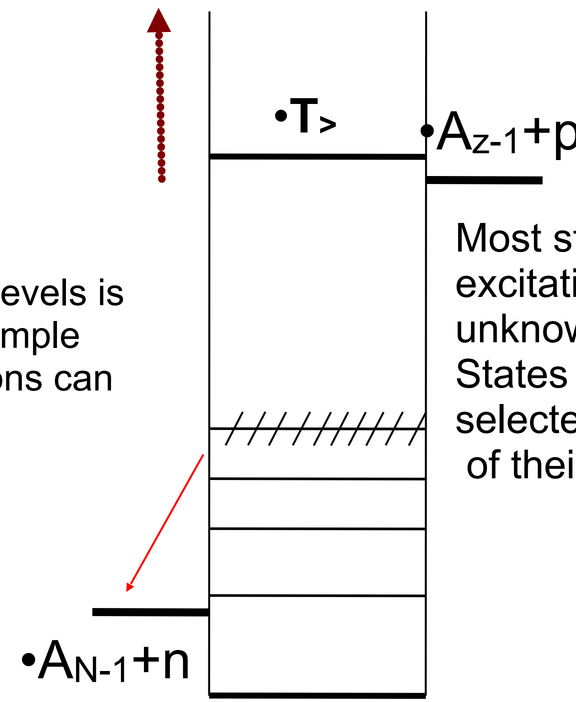
- Proton rich exotic



- Density of levels is low. Even simple considerations can work

^{14}F-? ^{13}O+ p → ^{14}F

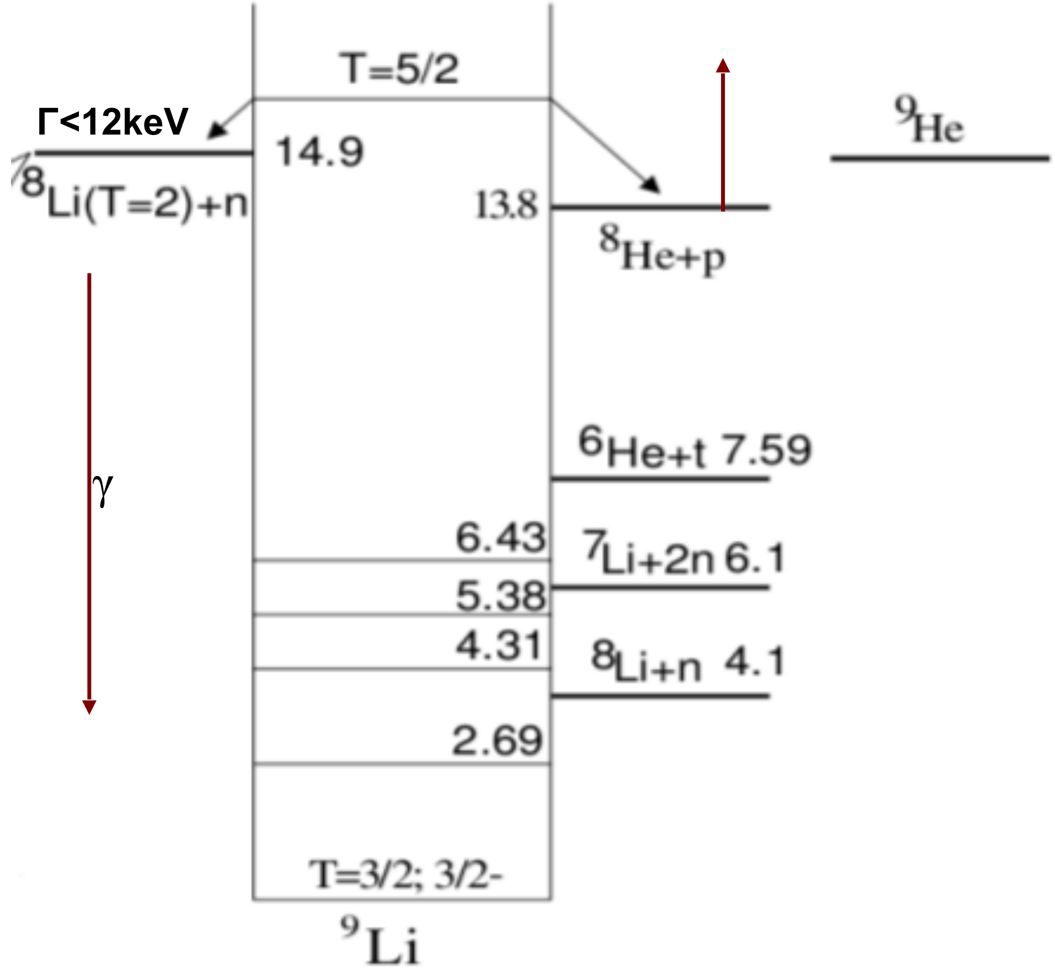
- Neutron rich exotic



Most states at high excitation energy are unknown.
States with T> selected because of their structure

- ^{9}He? ^{8}He+p→ ^{9}Li (T=5/2)
- instead of ^{8}He+n

$$\Psi_{^9\mathrm{Li}(T=5/2)} = \frac{1}{\sqrt{5}}\Psi_{^8\mathrm{He}+p} + \frac{2}{\sqrt{5}}\Psi_{^8\mathrm{Li}(T=2)+n}\,.$$

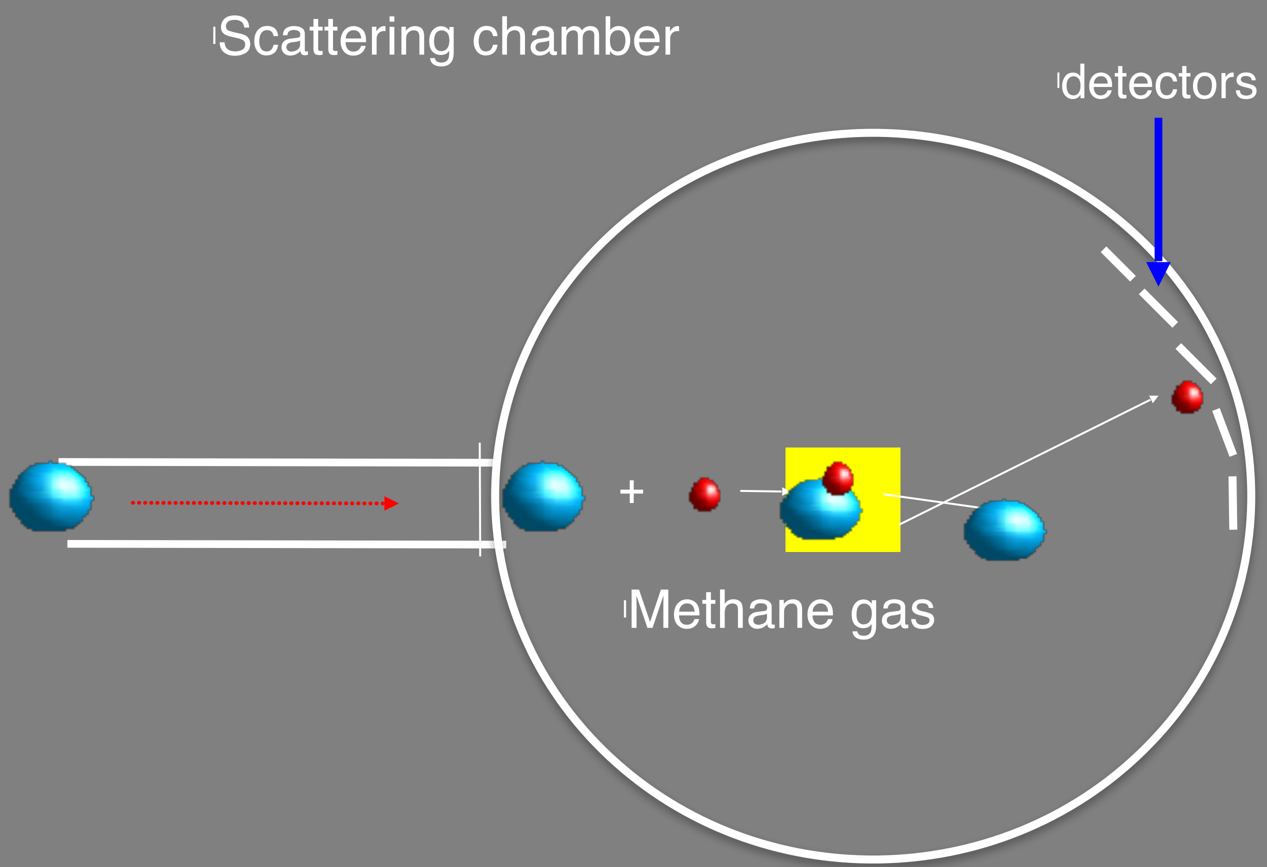


The ^{9}Li level scheme in the vicinity of the T=5/2 state

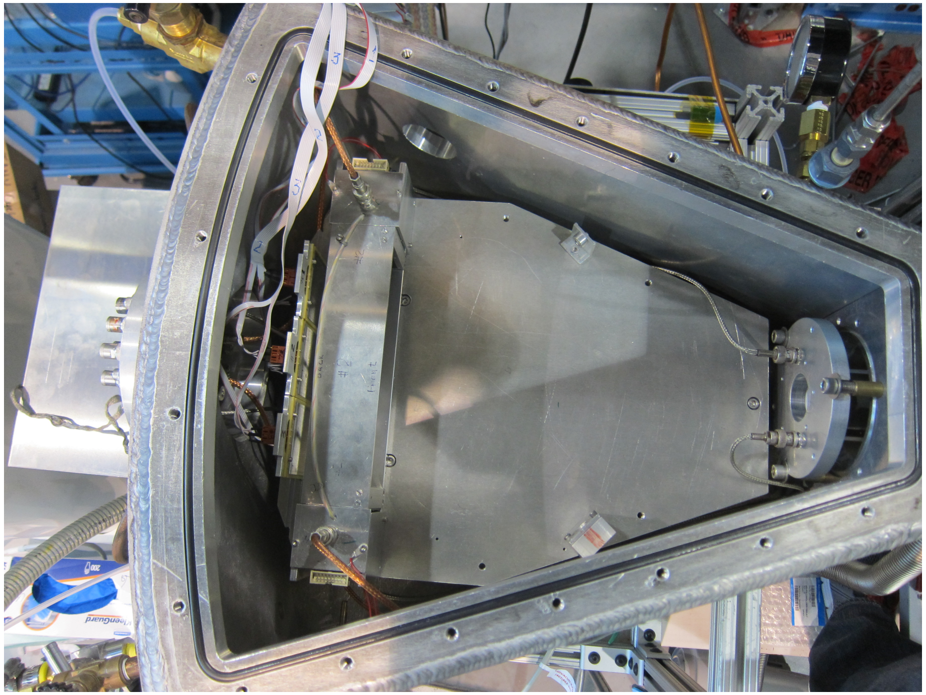
V.Z.Goldberg ENAM98 AIP C P 455

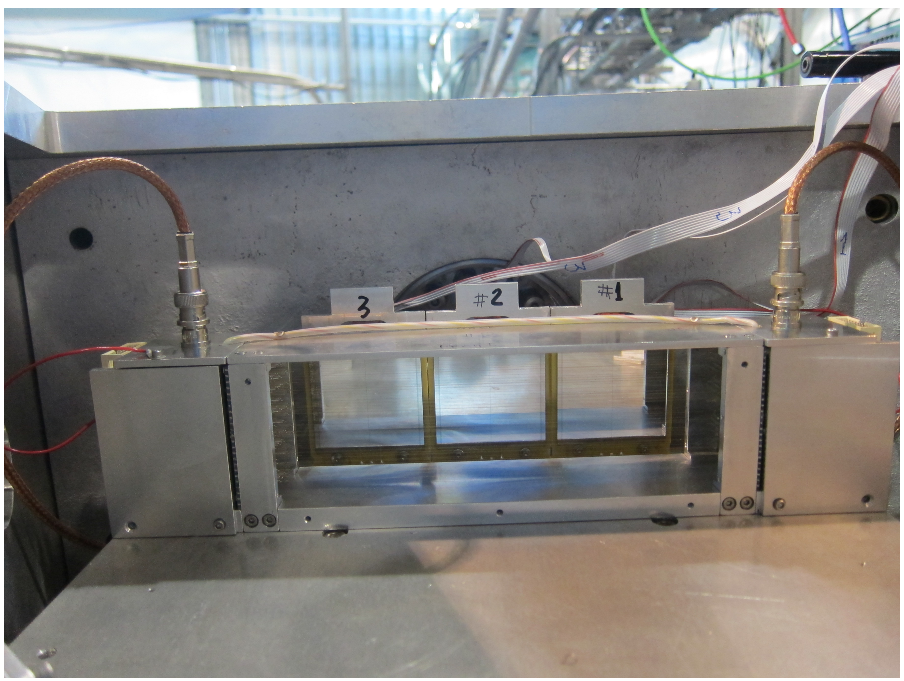
Inverse geometry and thick target technique

- 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



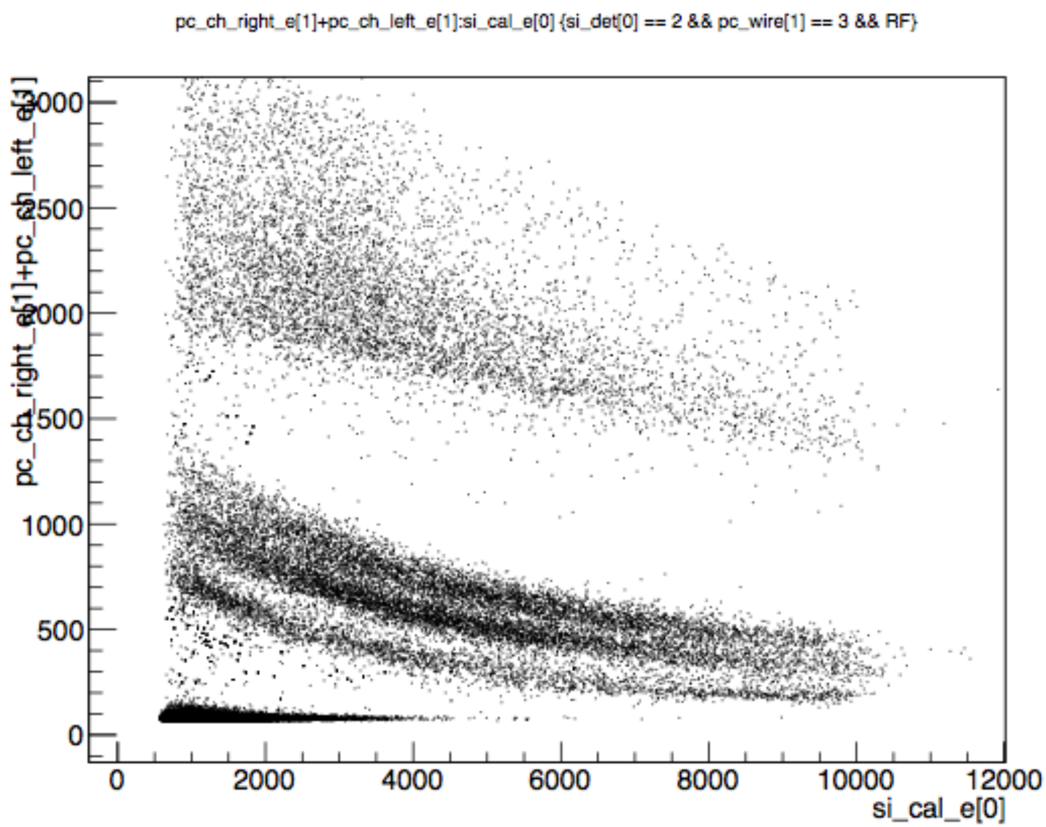
K.P.Artemov etal., Yad.Fiz. 52, 634 (1990); Sov.J.Nucl.Phys. 52, 408 (1990)

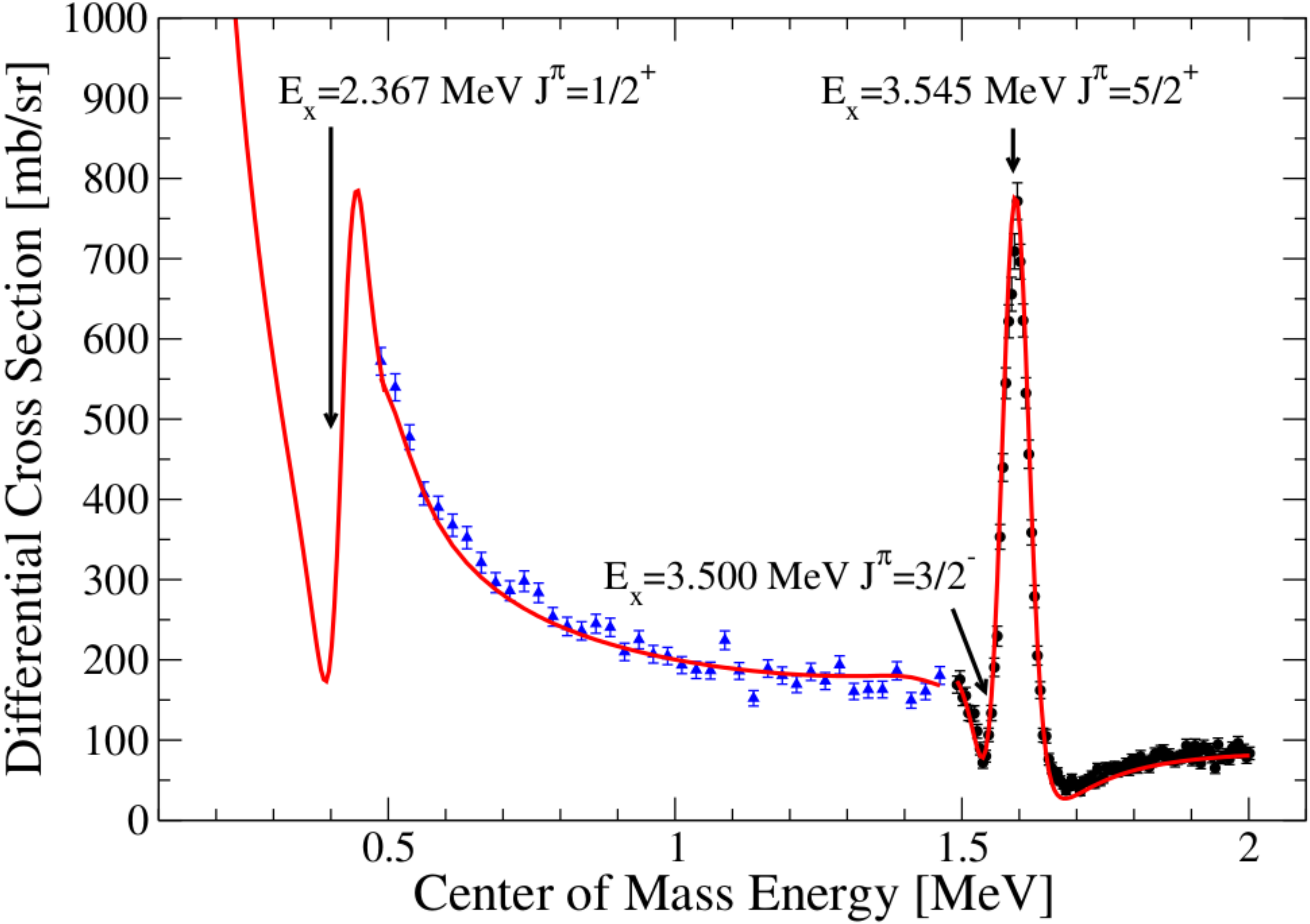




^{8}He+p resonance scattering at TRIUMF (July 2014).

dE/dx-E spectrum

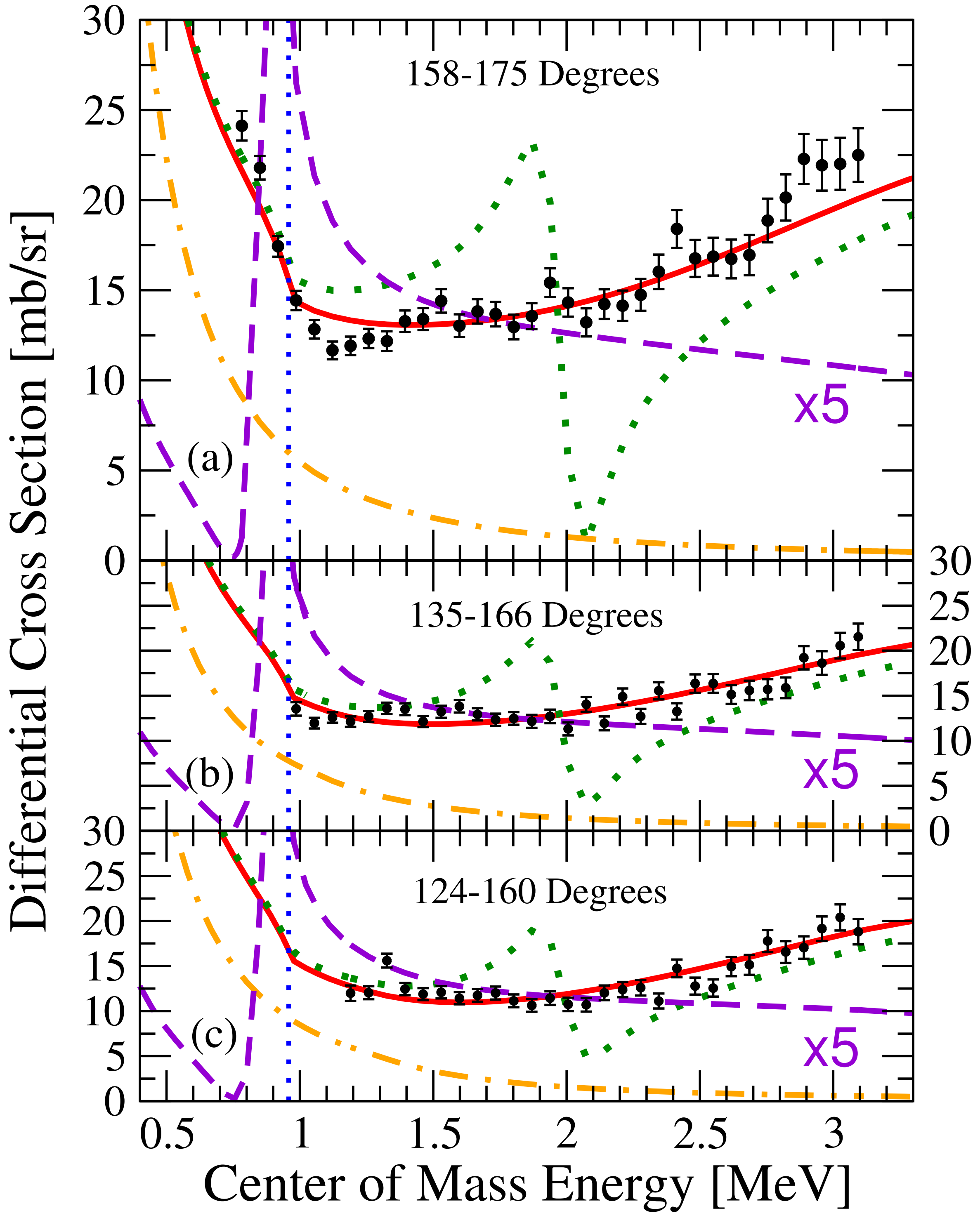




E_x=2.367 MeV J^π=1/2$^+$
E_x=3.545 MeV J^π=5/2$^+$
E_x=3.500 MeV J^π=3/2$^-$
Differential Cross Section [mb/sr]
Center of Mass Energy [MeV]
0
100
200
300
400
500
600
700
800
900
1000
0.5
1
1.5
2

^{8}He(p,p) results

Angular distributions are isotropic (low energy)
Except for the low energy rise (the Wigner cusp), the distributions are featureless; no sign of a narrow *s*-wave or *p*-wave resonances

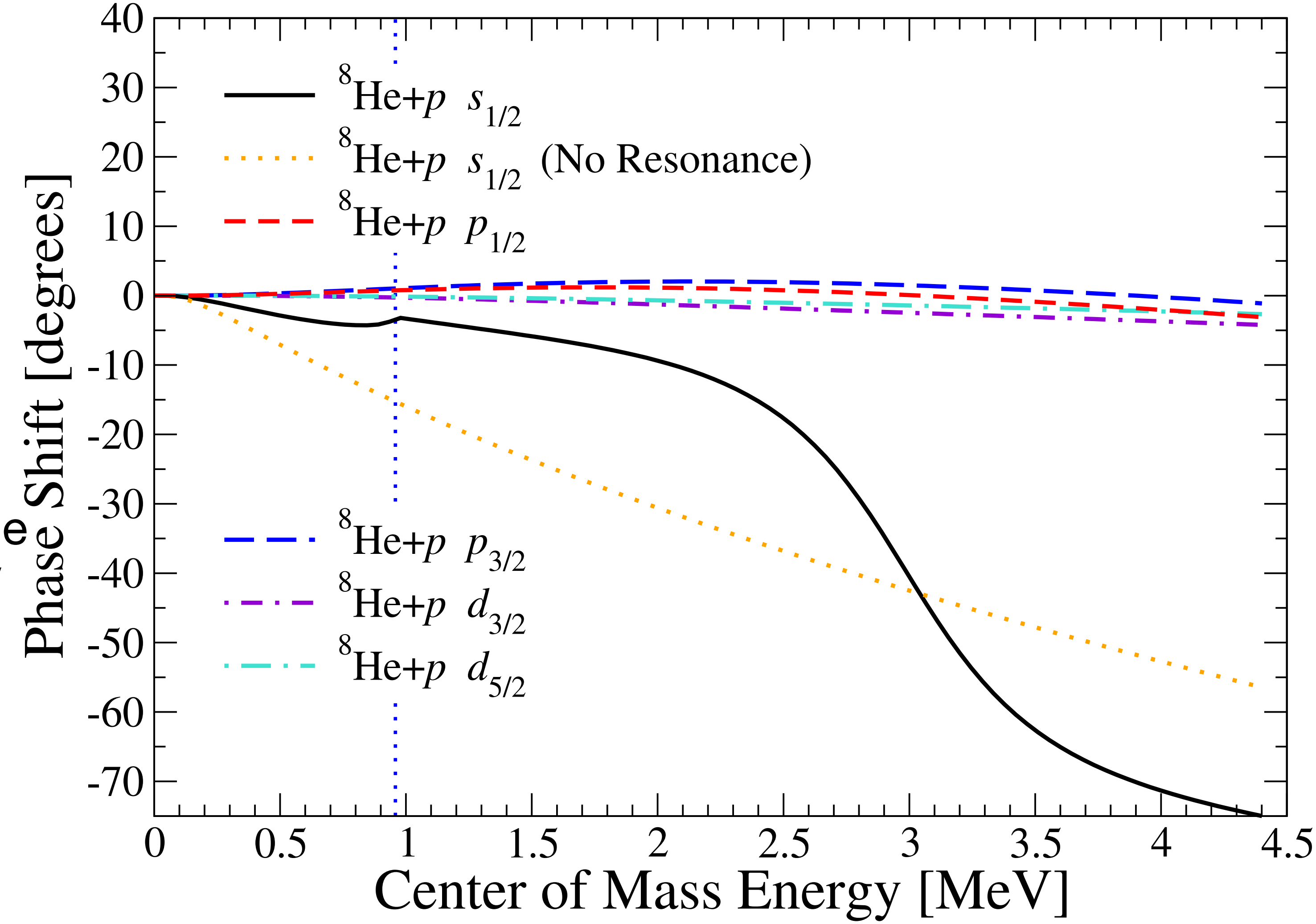


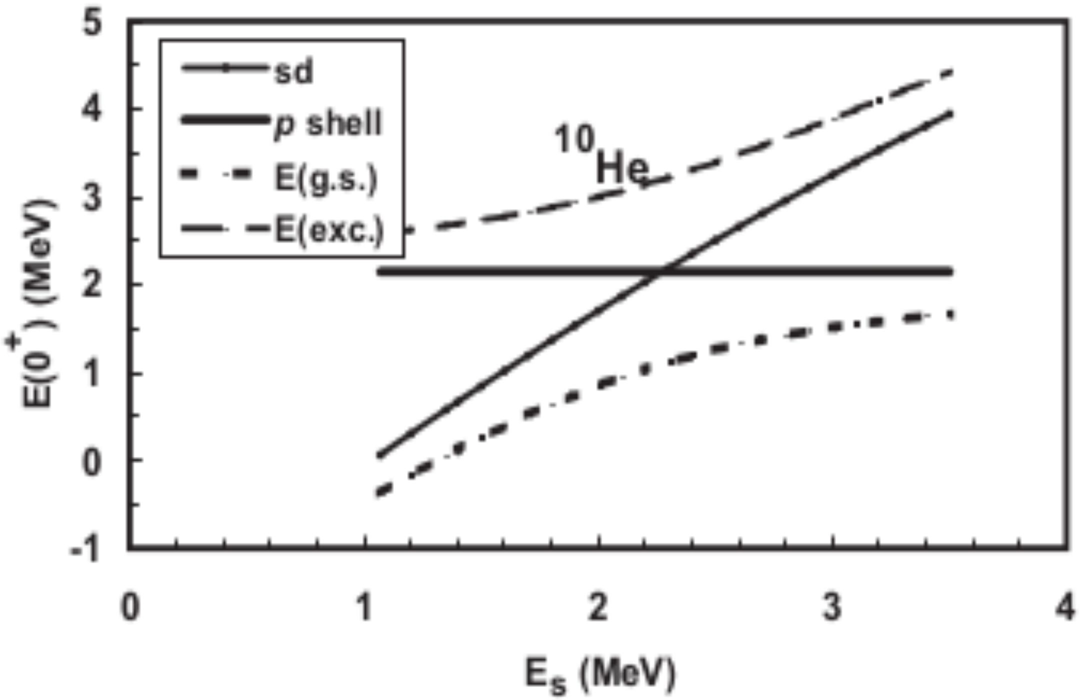
^{8}He(p,p) results

Strong evidence for $1/2^{+}$ T=5/2 broad (~3.5MeV) resonance at 17.1 MeV excitation energy in ^{9}Li (and for the isospin conservation)

9He should be unstable to n decay by 2.9 MeV

Narrow p (1/2-) state? To be unobservable





In 10He, plotted vs Es in 9He are the energies of the p-shell +0 state (wide solid line), the (sd)2 0+ state computed herein (thin solid curve), and the resulting energies of the g.s. (short-dashed curve) and excited 0+ state (long-dashed curve), assuming a mixing matrix element of V = 1.05 MeV (see text).

^{9}He Summary

Good counting statistics and good energy resolution search for T=5/2 states in ^{9}Li was made. No narrow resonances were found.
Observed Wigner cusp is a sure indication for a broad $1/2^{+}$ resonance.
It leads to the (ground) state in ^{9}He of ~3 MeV unstable to neutron decay.
On this ground one might predict two 0^{+} states in ^{10}He; the ground state being unstable to a neutron decay by ~1.5 MeV.
The resonance investigation of the $T_{>}$ states using rare beams is a rather new approach, but could be a powerful instrument to study properties of neutron rich exotic nuclei.

The possession of knowledge does not kill the sense of wonder and mystery.
There is always more mystery.
- Anais Nin

Coauthors in the study of T=5/2 states in ^{9}Li

E. Uberseder[1], G.V. Rogachev[1],[1]E. Koshchiy,[1]B.T. Roeder, M.Alcorta[2] , G. Chubarian[1] , B. Davids[2], C. Fu[3] J. Hooker[1], H. Jayatissa[1], D.Melconian[1], and R.E. Tribble[1]

[1]Department of Physics & Astronomy and Cyclotron Institute,
Texas A&M University, College Station, TX 77843, USA
[2]TRIUMF, Vancouver, Canada [3]Shanghai Jiao Tong University, Shanghai, China

THANK YOU

Dr. G. Rogachev

Dr. R. Tribble

Dr.s M. Avila, V.Z. Goldberg, and E. Johnson

Dr. Changbo Fu

Dr. E. Koshchiy

Dr. G. Rogachev

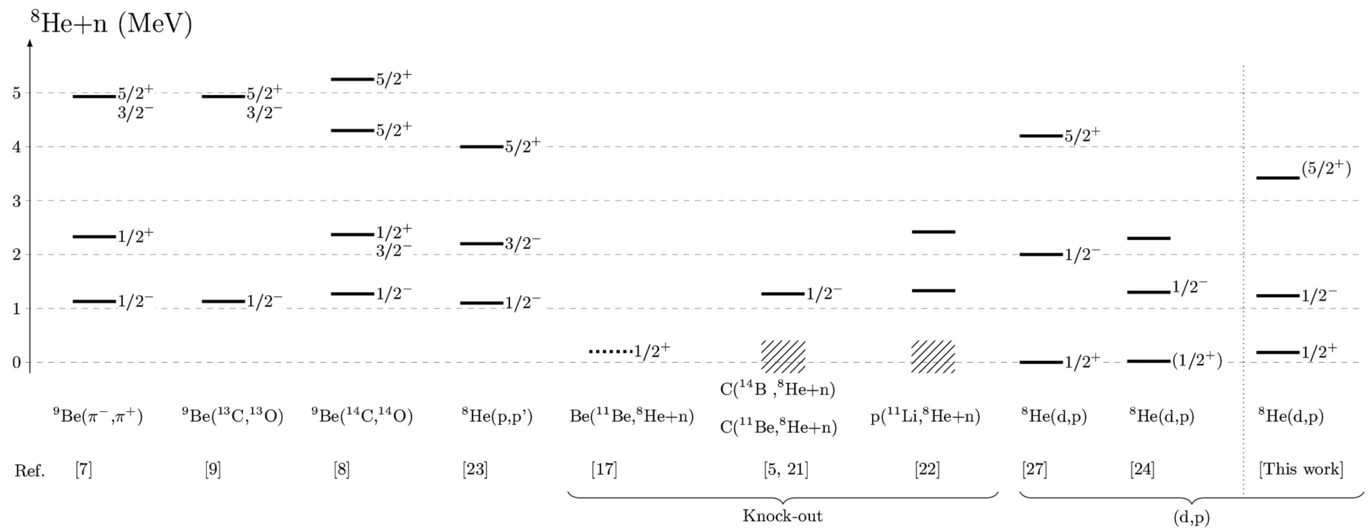
Dr. R. Tribble

Dr.s M. Avila,
V.Z. Goldberg,
and E. Johnson

Dr. C. Fu

History of ^{9}He Measurements

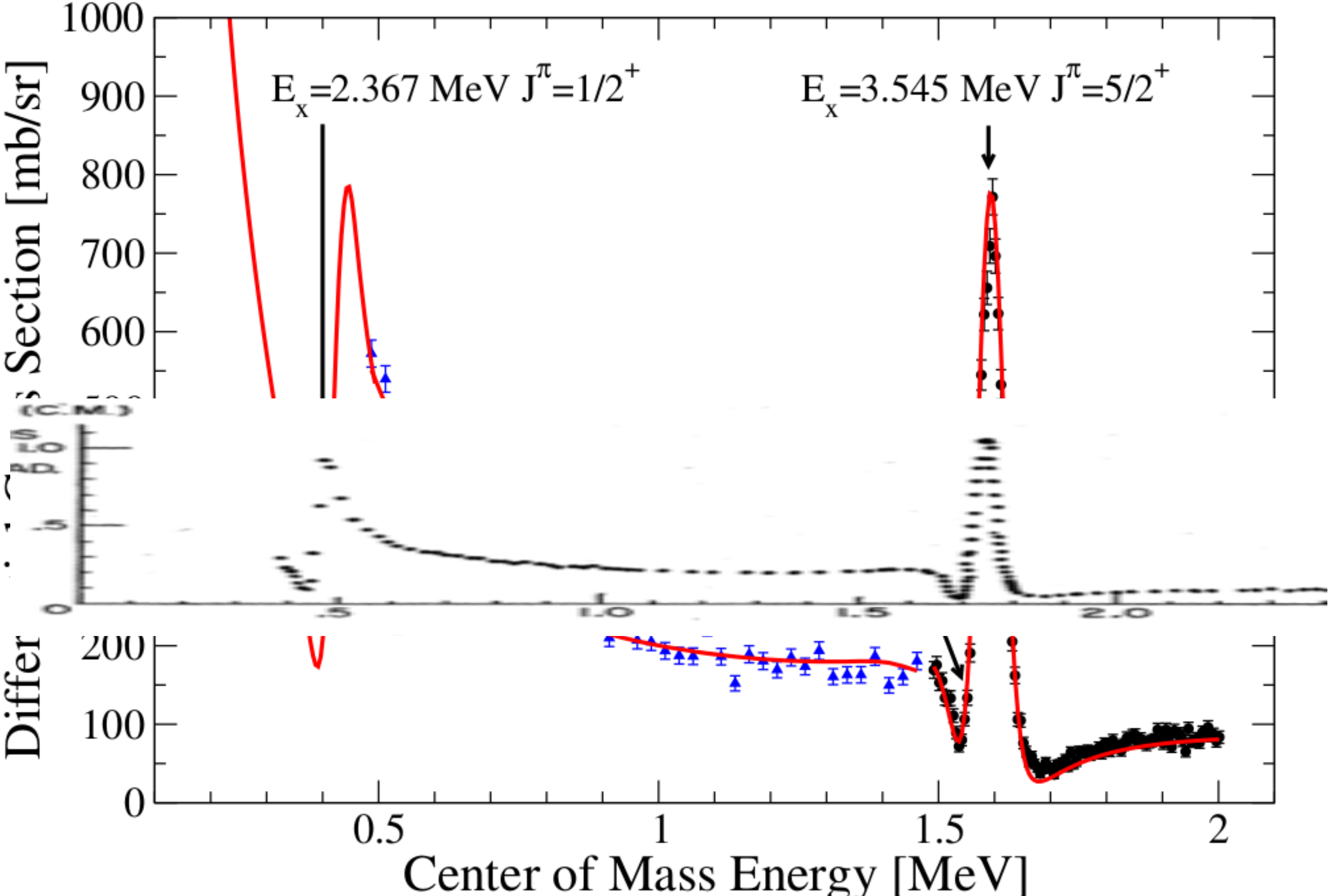
Accessing ^{9}He directly is experimentally difficult



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

- Previous measurements show evidence for parity inversion
- First two states are claimed to be:
  1. $J^\pi = 1/2^+$ state 200 keV above neutron separation energy (Γ=200 keV)
  2. $J^\pi = 1/2^-$ state 1.3 MeV above neutron separation energy (Γ=130 keV)
- Measurements suffer from poor resolution or poor statistics (or both)

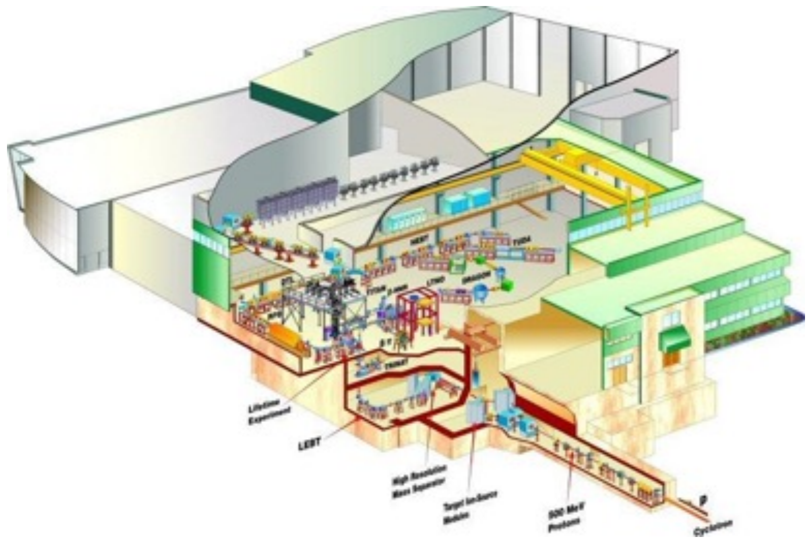
Findings are not reconcilable with nuclear theory!



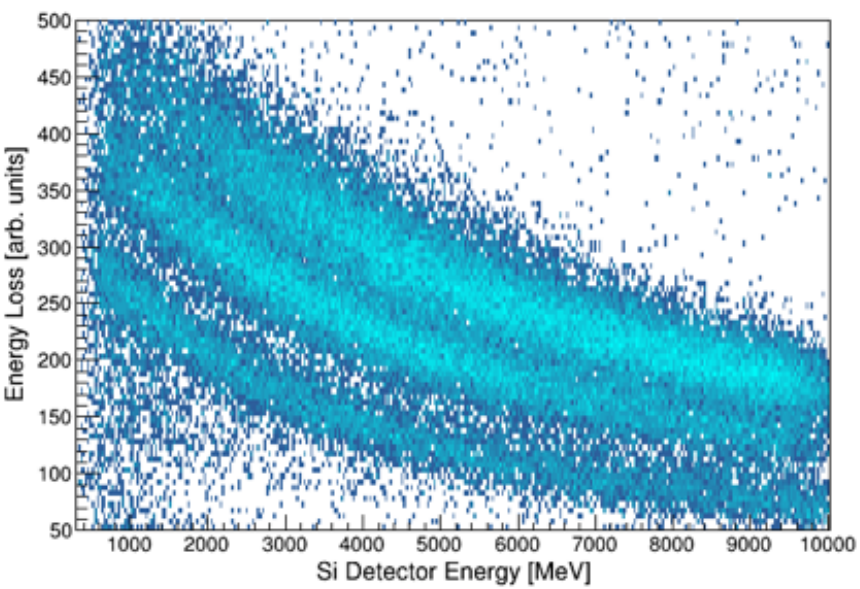
Differential Cross Section [mb/sr]
Center of Mass Energy [MeV]
E_x=2.367 MeV J^π=1/2^+
E_x=3.545 MeV J^π=5/2^+
(C.M.)

^{8}He(p,p)^{8}He Measurement

- Experiment performed at ISAC-II facility at TRIUMF
  - 500 MeV proton beam impinges on production target
  - ^{8}He produced using ISOL technique and reaccelerated via a superconducting linac to 4 AMeV
  - Excellent beam energy resolution and purity
  - ^{8}He impinged on 990 torr of methane gas

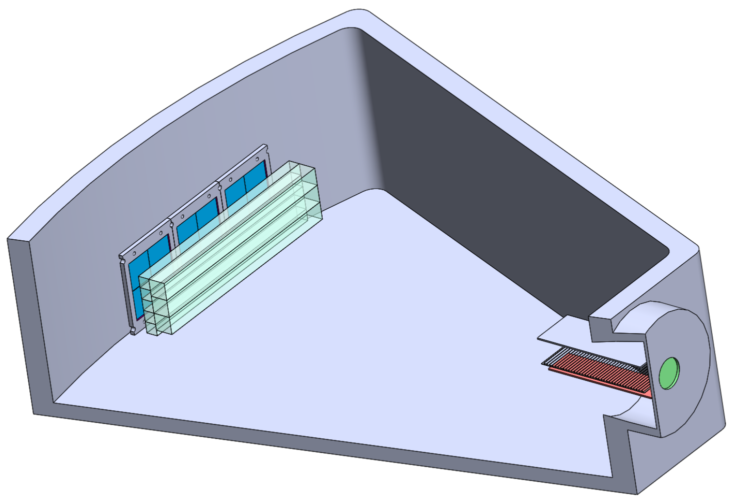


http://www.triumf.ca/research-program/research-facilities/isac-facilities



Clean identification of recoil protons from deuterons using PSPC and Si detectors over all excitation energies

Experimental Setup



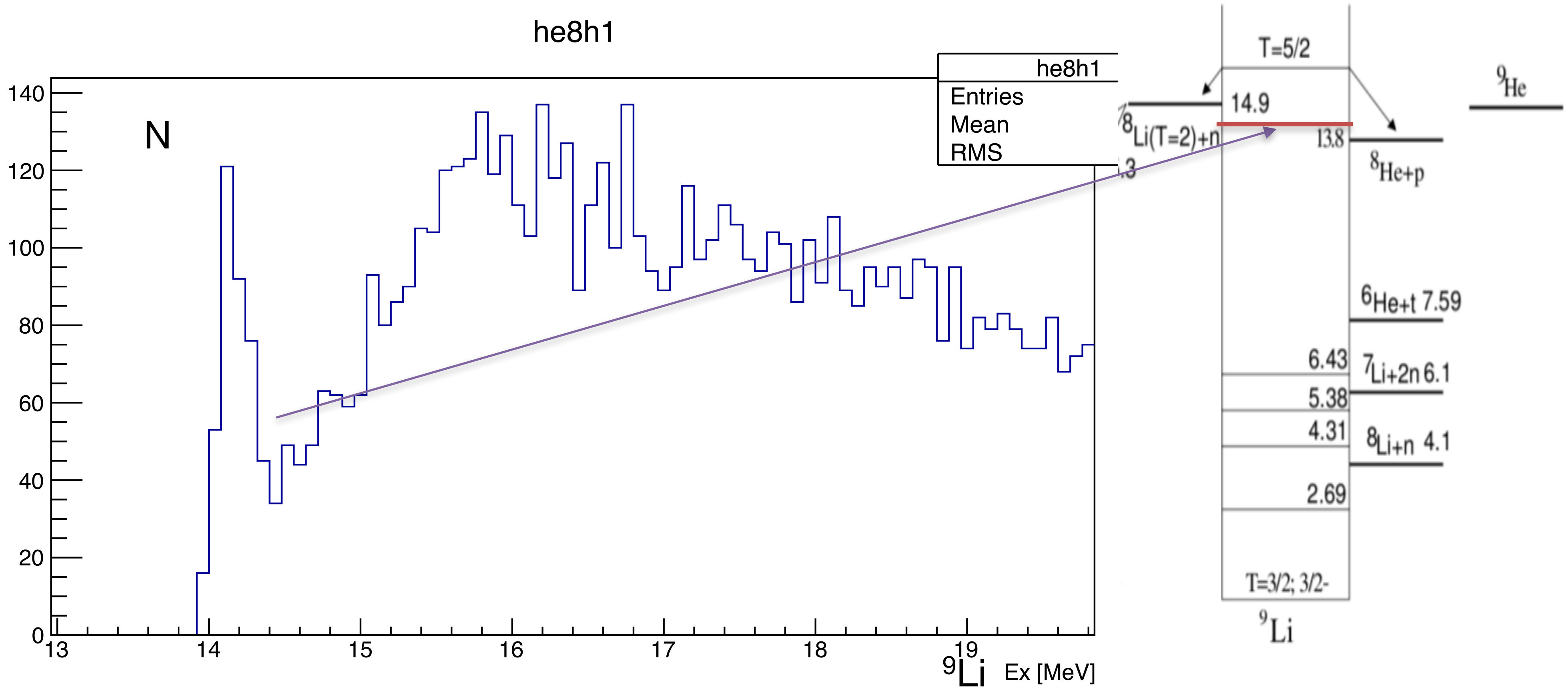
Thick Target Inverse Kinematics Technique

- Beam enters chamber and is stopped in the gas volume
- If scattering event occurs, proton recoils forward to detectors
- Measure excitation spectrum with a single beam energy and high efficiency (good for radioactive beams!)

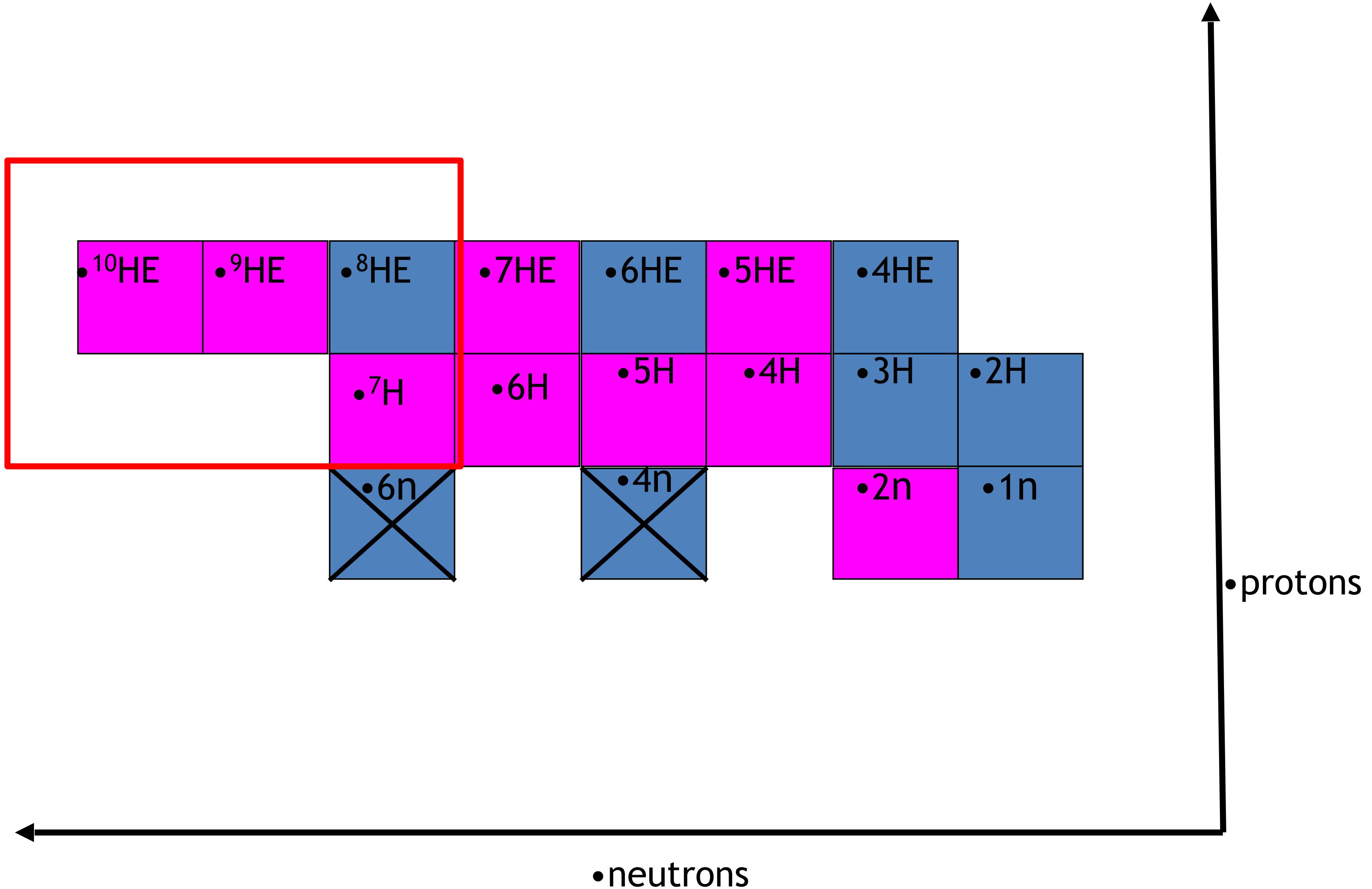
Active Detection Elements

1. 3 quad-segmented forward silicon detectors (total energy)
2. 8 position sensitive proportional counters (energy loss and angle reconstruction)
3. Windowless ionization chamber (normalization and incoming identification)

R. J. Charity et al., Phys.Rev. C 78, 054307 (2008)



Experimental excitation-energy distributions for
9Li fragments from p-8He correlations. H, C(12Be, X), E=50 MeV/nucleon



10HE
9HE
8HE
7HE
6HE
5HE
4HE
7H
6H
5H
4H
3H
2H
6n
4n
2n
1n
protons
neutrons

Hydrogen isotopes references:

Review: A. I. Baz', V. I. Goldanskii, V. Z. Goldberg, and Ya. B. Zel'dovich, Light and Intermediate Nuclei Close to the Drip Line (Nauka, Moscow, 1972) [in Russian].

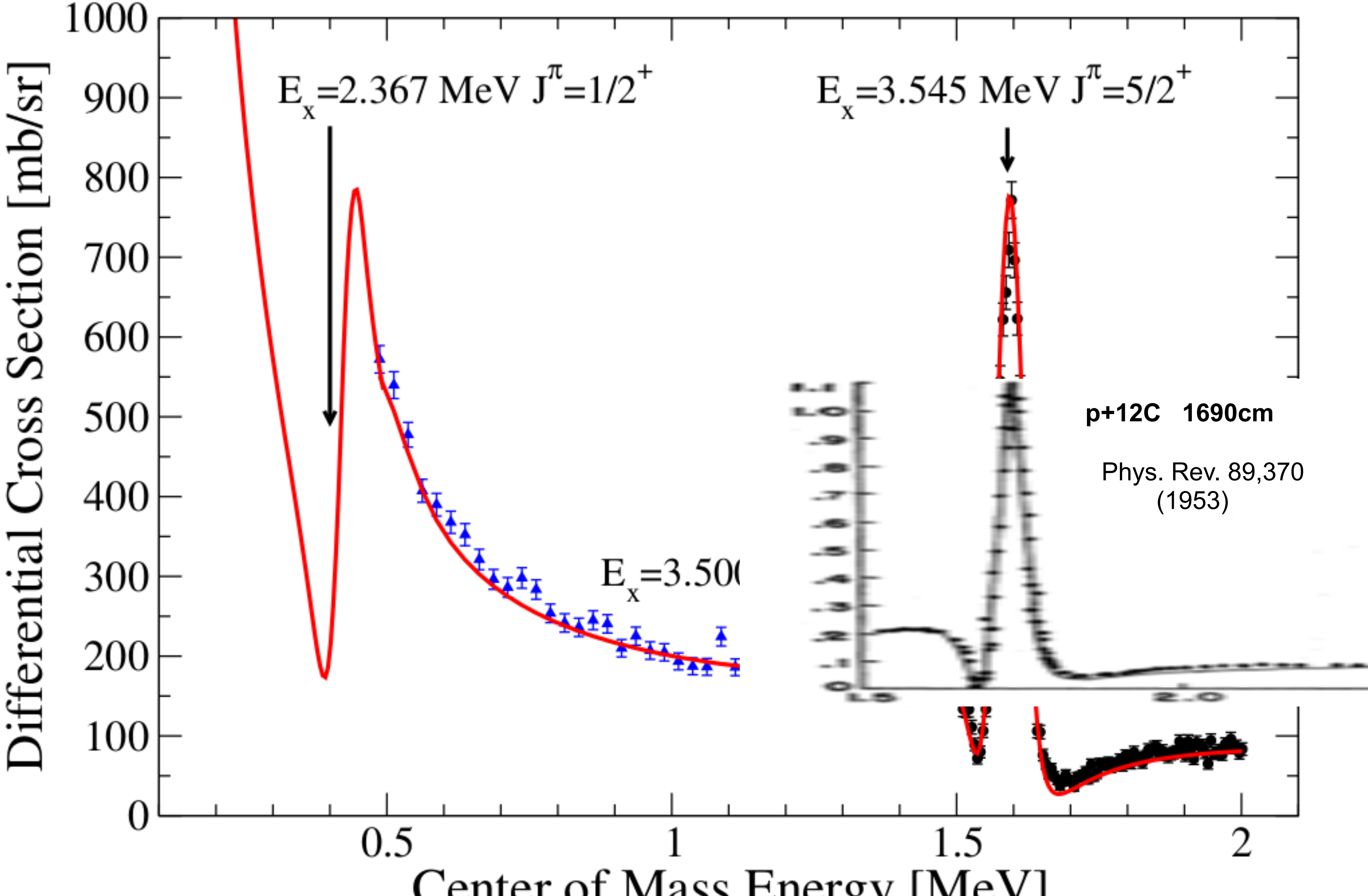
Review 4H-7H:Yu.B. Gurov, S.V. Lapushkin, B.A. Chernyshev, V.G. Sandukovsky, Phys. of Part. and Nucl., 2009, Vol. 40, p. 558

4H D. R. Tilley, H. R. Weller, and G. M. Hale, Nucl. Phys. A 541, 1 (1992).

5H M. S. Golovkov et al., Phys. Rev. C 72, 064612 (2005)

6H D. V. Aleksandrov et al., Yad. Fiz. 39, 513 (1984) [Sov. J. Nucl. Phys. 39, 323 (1984)].
A. V. Belozerov et al., Nucl. Phys. A 460, 352 (1986).

7H A. A. Korsheninnikov et al., Phys. Rev. Lett. 90, 082501 (2003).
M. S. Golovkov et al., Phys. Lett. B 588, 163 (2004). ;E. Yu. Nikolskii et al., Phys. Rev. C81,064606(2010), M. Caamano et al., PRL99, 062502 (2007)


Differential Cross Section [mb/sr]
Center of Mass Energy [MeV]
E_x=2.367 MeV J^π=1/2$^+$
E_x=3.545 MeV J^π=5/2$^+$
E_x=3.50
p+12C 1690cm
Phys. Rev. 89,370
(1953)

MYSTERY OF ^{9}He, EXOTIC NEUTRON RICH LIGHT NUCLEI, AND A WAY TO STUDY THESE THROUGH THEIR ISOBAR ANALOG STATES

Goldberg V.Z.[1], Rogachev G.[1], Uberseder E.[1], Roeder B.[1], Koshchiy[1], Melconian D.[1], Chubarian G.[1], Hooker J.[1], Jayatissa H.[1], Alcorta M.[2], Davids B.[2], Fu C.[3], Tribble R.[1]

[1] Texas A&M University, USA; [2] TRIUMF, BC, Canada;
[3] Shanghai Jiao Tong University, China
E-mail: goldberg@comp.tamu.edu

The original interest to the ^{9}He spectrum is evidently related with an unusual *N* to *Z* ratio which is 3.5. Beginning with ^{9}He, all heavier isotopes of He are unstable to neutron decay. During the last 25 years the properties of the lowest states in ^{9}He were under intensive experimental and theoretical investigation. It appears that the nuclear structure of these states ($1/2^+$ and $1/2^-$) can't be explained on the ground of our knowledge of conventional nuclei. The most evident problem is the width of the $1/2^-$ resonance, which (naively) should be expected to be a shell model *p*1/2 state. Indeed, different experiments (see [1] for the history of the theoretical and experimental studies), including a recent one [1] of well studied (d,p) reaction induced by a rare ^{8}He beam, claimed a narrow (~100 keV) $1/2^-$ first excited state. Various model calculations and even recent *ab initio* approaches [2] could not reproduce experimental results giving ten times larger widths for the $1/2^-$, as would be naive expectations. This clear contradiction between experiment and contemporary theory could be a sign of an unusual nuclear structure at the border of nucleon stability.

Therefore we used a relatively novel experimental technique of obtaining information on neutron rich exotic nuclei through their analog states in neighboring nuclei populated in resonance reactions with rare beams. We have made measurements of the ^{8}He+p resonance elastic scattering to obtain information on *T*=5/2 levels in ^{9}Li. We used ^{8}He beam with energy of 4MeV/*A* and intensity ~10^4 pps provided by the TRIUMF facilities. The measurements of the excitation function were made by Thick Target Inverse Kinematics method [3–5] (TTIK). The approach and the high quality of the TRIUMF beam enable us to study the isobaric analogs of the ^{9}He states even if ^{9}He was barely unbound or even bound by few tens of keV.

As a result, our high resolution and high counting statistics study of the excitation functions for the ^{8}He+p elastic scattering did not reveal any narrow structures which could be related with the claimed states in ^{9}He. However we observed a strong Wigner cusp at the threshold of decay of ^{9}Li into the ^{8}Li(T=2,0^+) + n channel. This finding gave evidence for the presence of a *l*=0 resonance as the isobar analog of the ^{9}He ground state. Evidently, these results show for a new binding energy of ^{9}He as well as different properties of its ground state. However, the accurate data should be provided in a framework of a developed *R* matrix approach in which the contribution of unknown $T_<$ resonances at ^{9}Li high excitation energy is addressed by an optical model potential [6]. This work should be finished soon.

I'll present the results of this work and its consequences for the considerations on some very exotic nuclei, like ^{10}He and ^{7}H. I'll consider the perspective of the present experimental approach for future studies.

1. T.Al Kalanee *et al.* // Phys. Rev. C. 2013. V.88. 034301.
2. K.M.Nollett // Phys.Rev. C. 2012. V.86. 044330.
3. K.P.Artemov *et al.* // Sov. J. Nucl. Phys. 1990. V.52. P.406.
4. V.Z.Goldberg // ENAM98. P.319.
5. G.V.Rogachev *et al.* // AIP Conf. Proc. 2010. V.1213. P.137.
6. D.Robson // Phys. Rev. 1965. V.137. P.535.