Unmasking halo features with two decades of ISOL beams @ TRIUMF

R. Kanungo
Saint Mary's University / TRIUMF

Breaking the traditional image

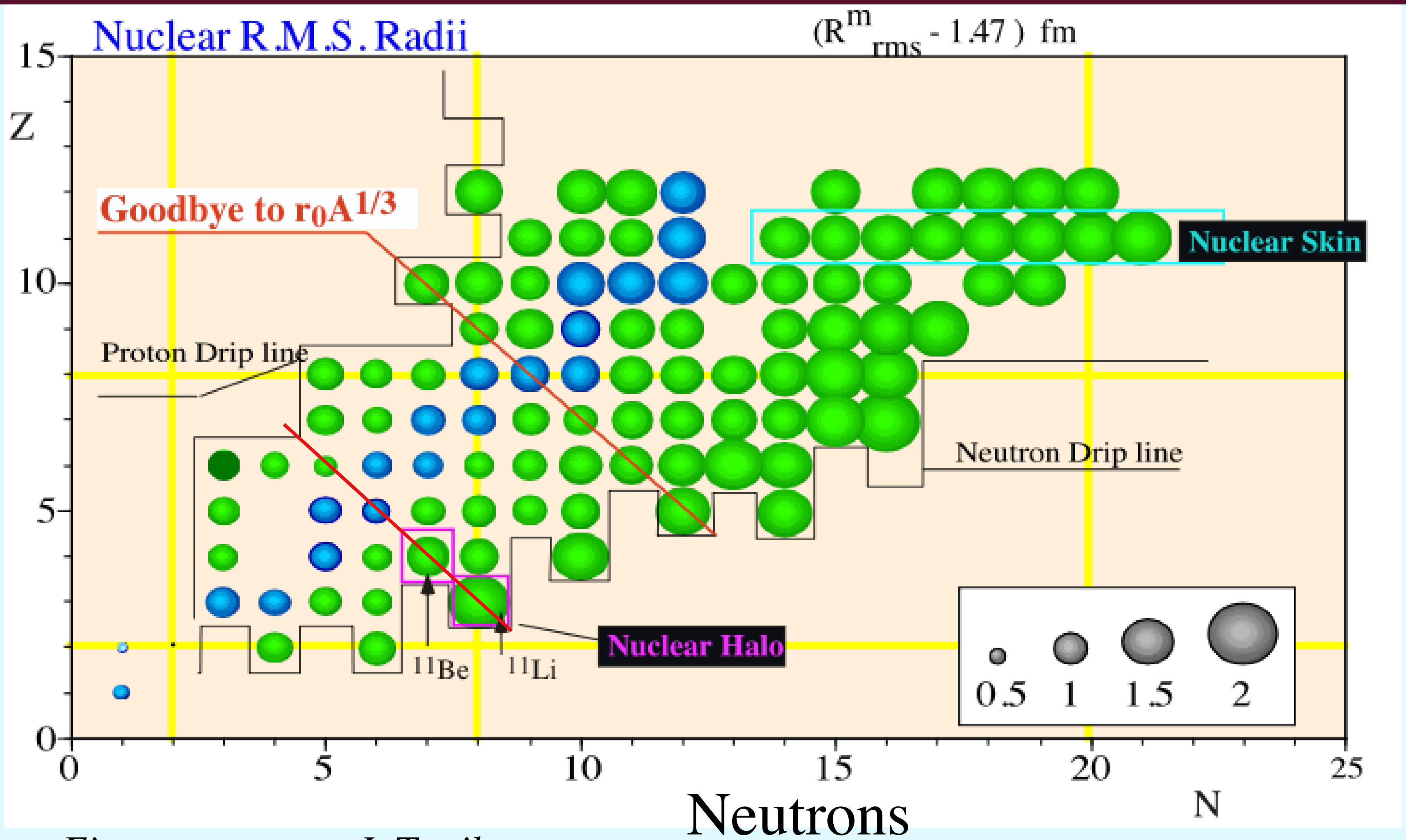
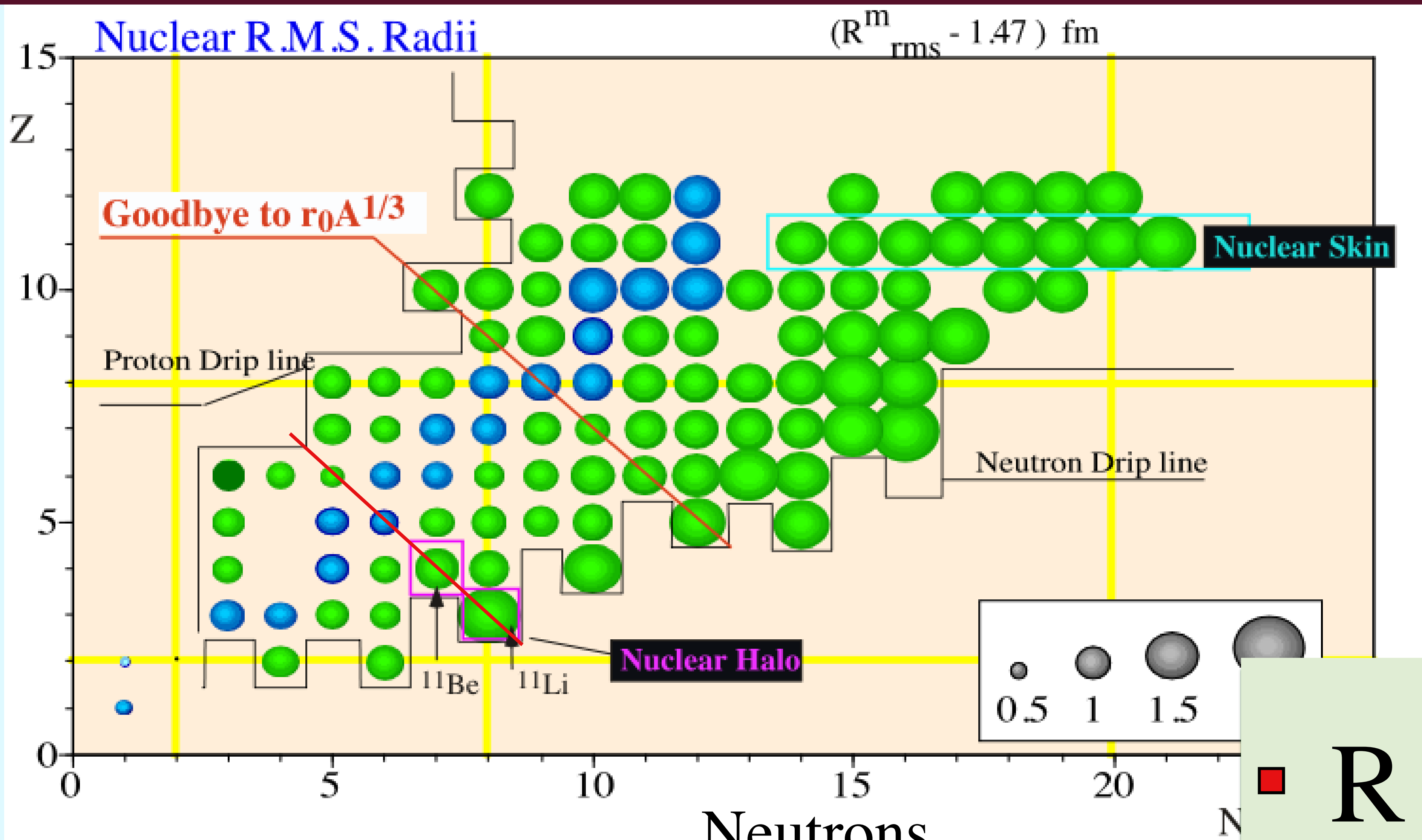


Figure courtsey : I. Tanihata

- Stable Isotope
- Rare Isotope

Breaking the traditional image



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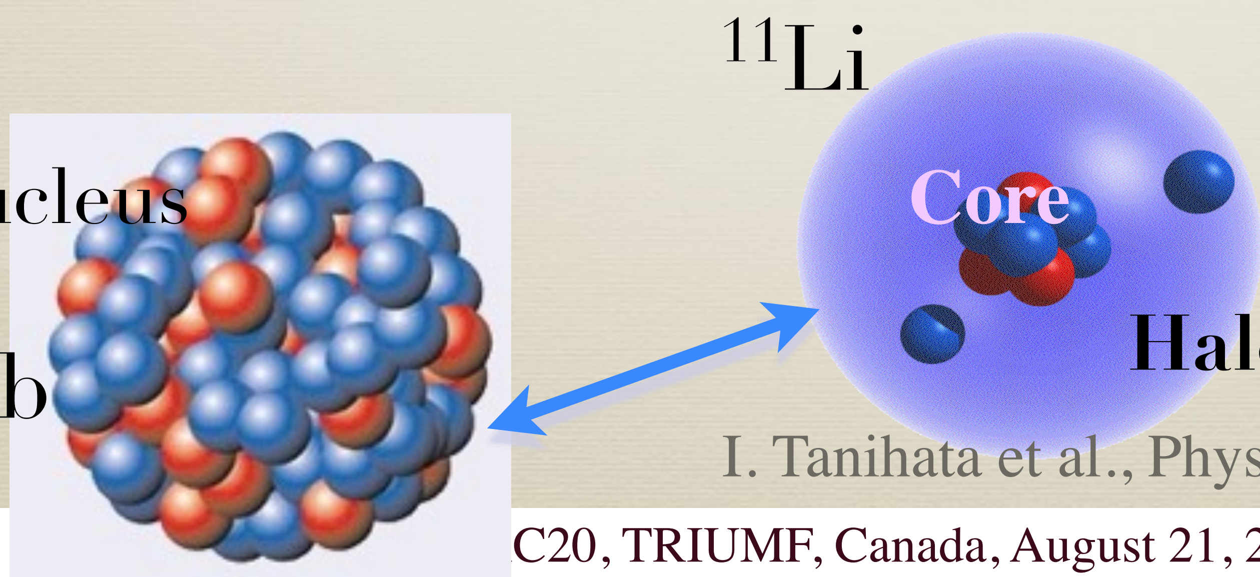
- $R \neq r_0 A^{1/3}$



I. Tanihata et al., Phys. Rev. Lett. 1985

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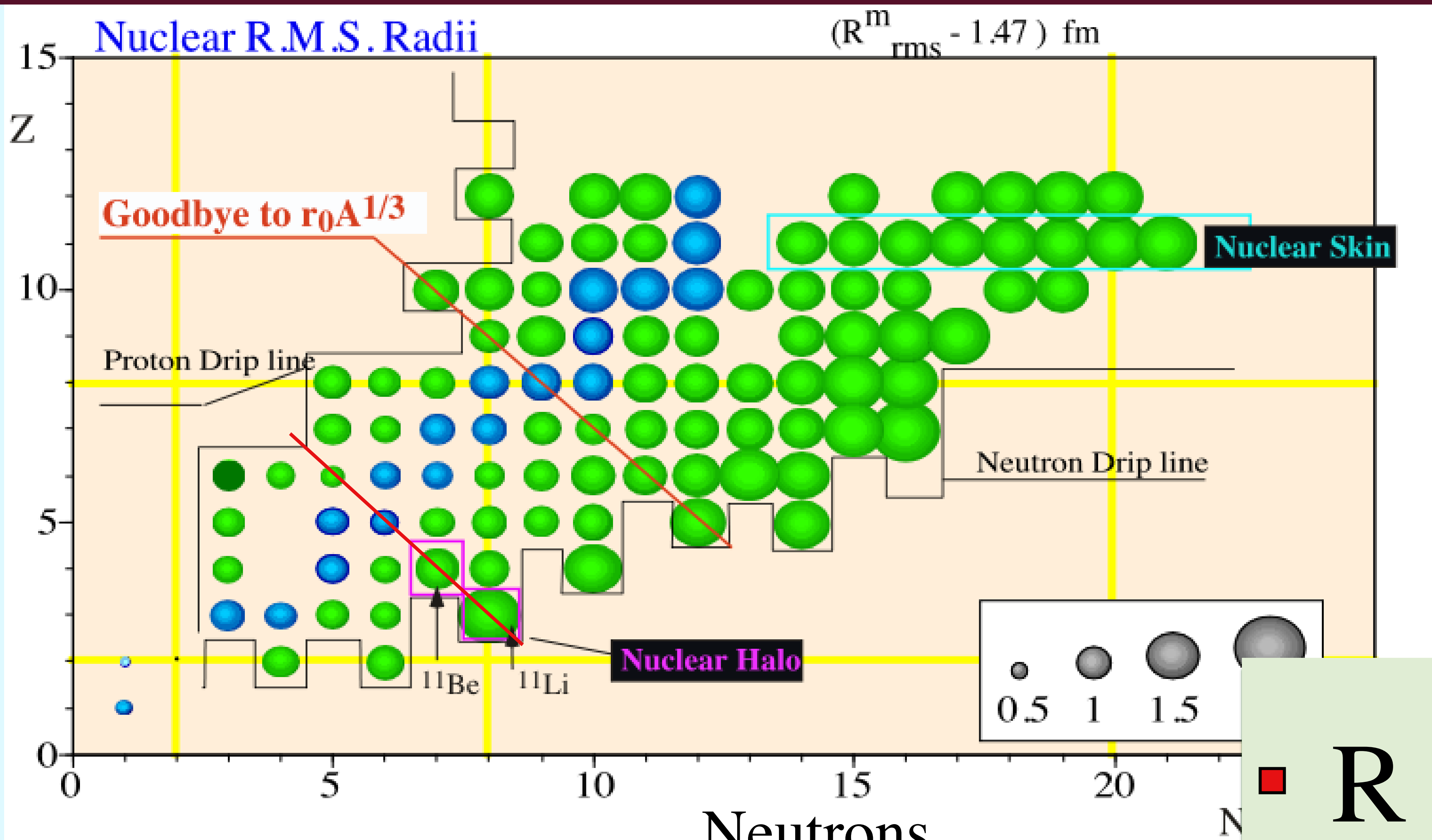


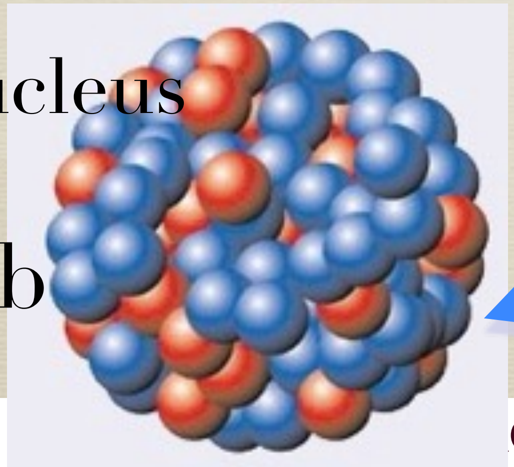
Figure courtsey : I. Tanihata

- Stable Isotope
- Rare Isotope

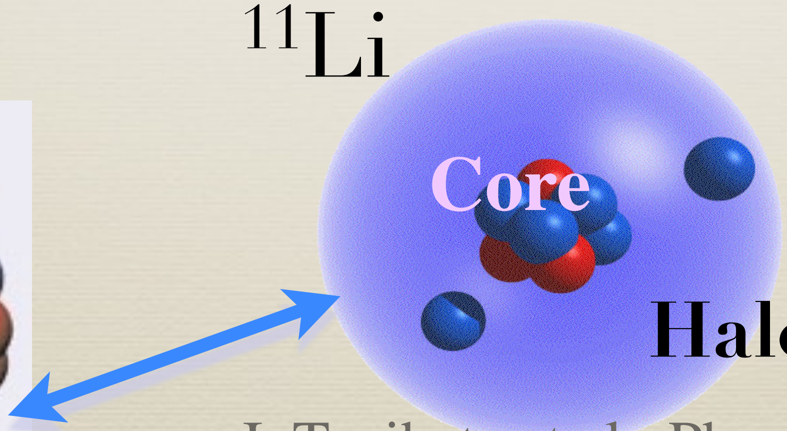
- $R \neq r_0\ A^{1/3}$
- Borromean-system
  Unique quantum system

Stable nucleus

^{208}Pb

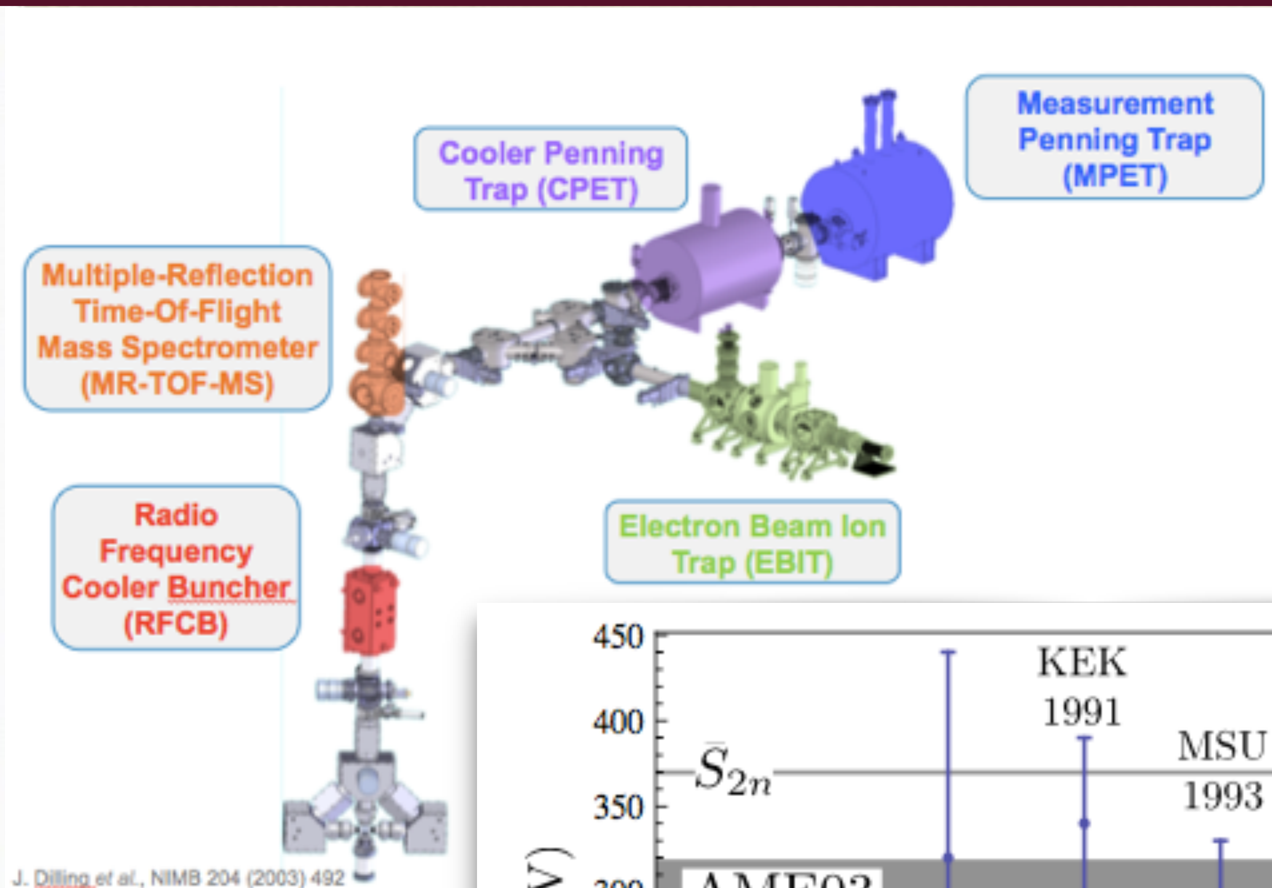


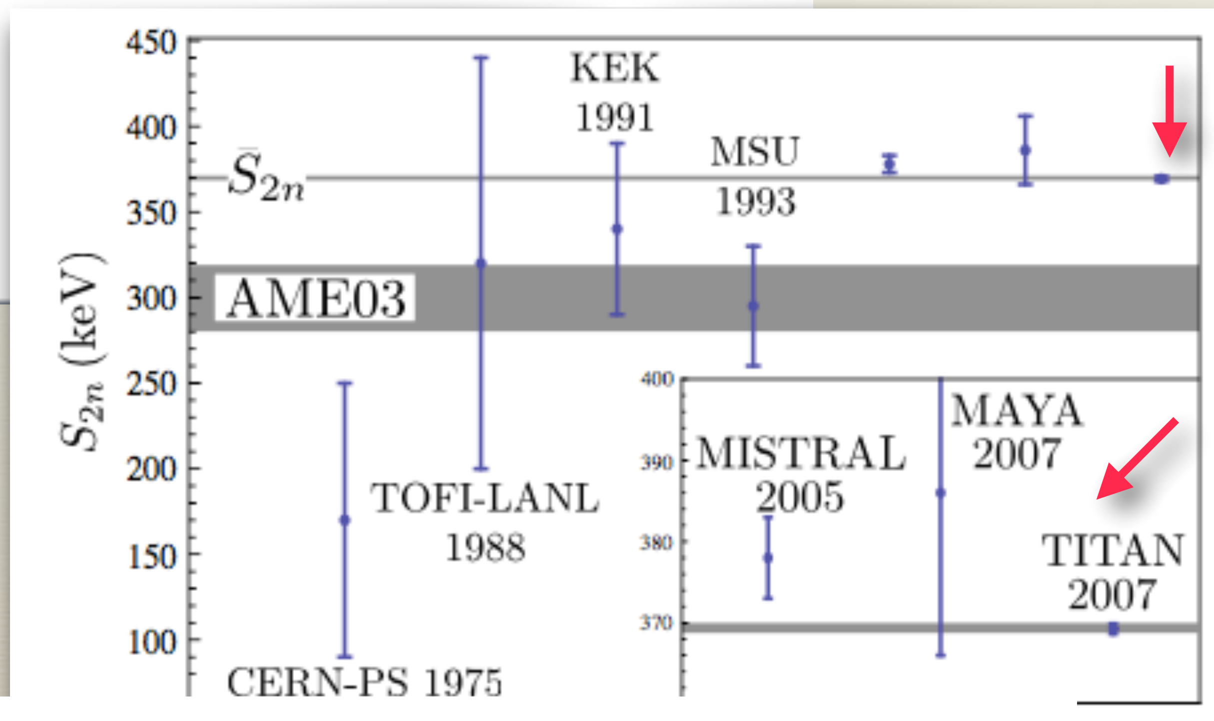
^{11}Li

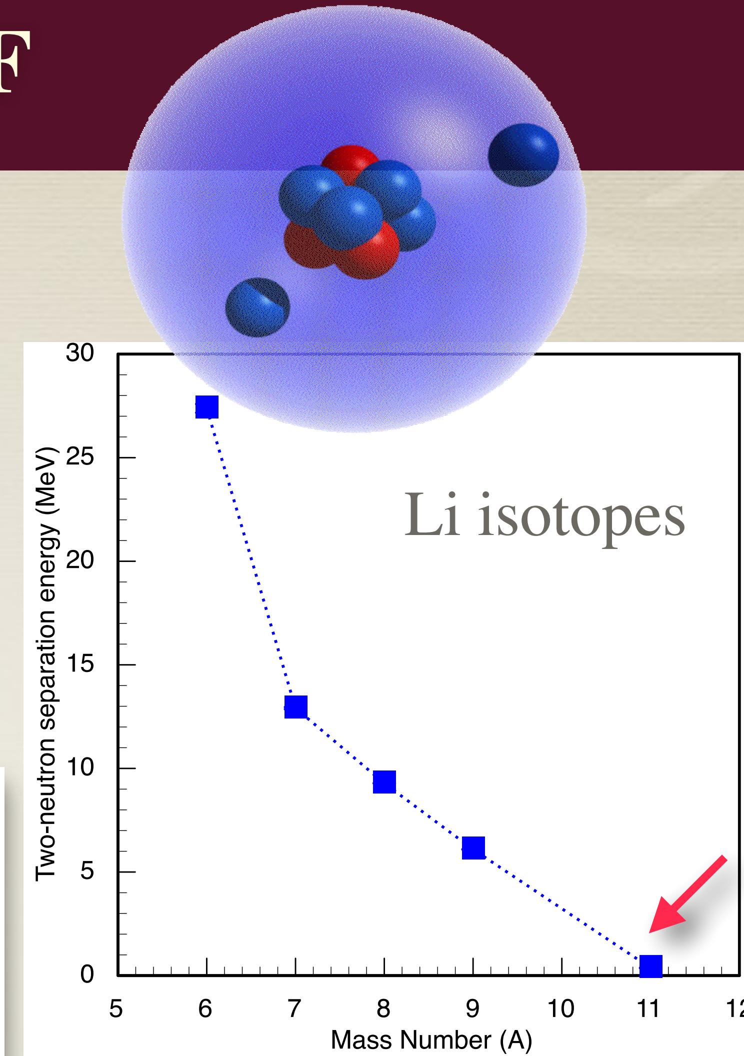


I. Tanihata et al., Phys. Rev. Lett. 1985

Weighing Halos - TITAN @ TRIUMF







PRL **101,** 202501 (2008) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2008

First Penning-Trap Mass Measurement of the Exotic Halo Nucleus ^{11}Li

M. Smith et al., PRL 101 (2008) 202501

Shortest half-life measured with Penning trap

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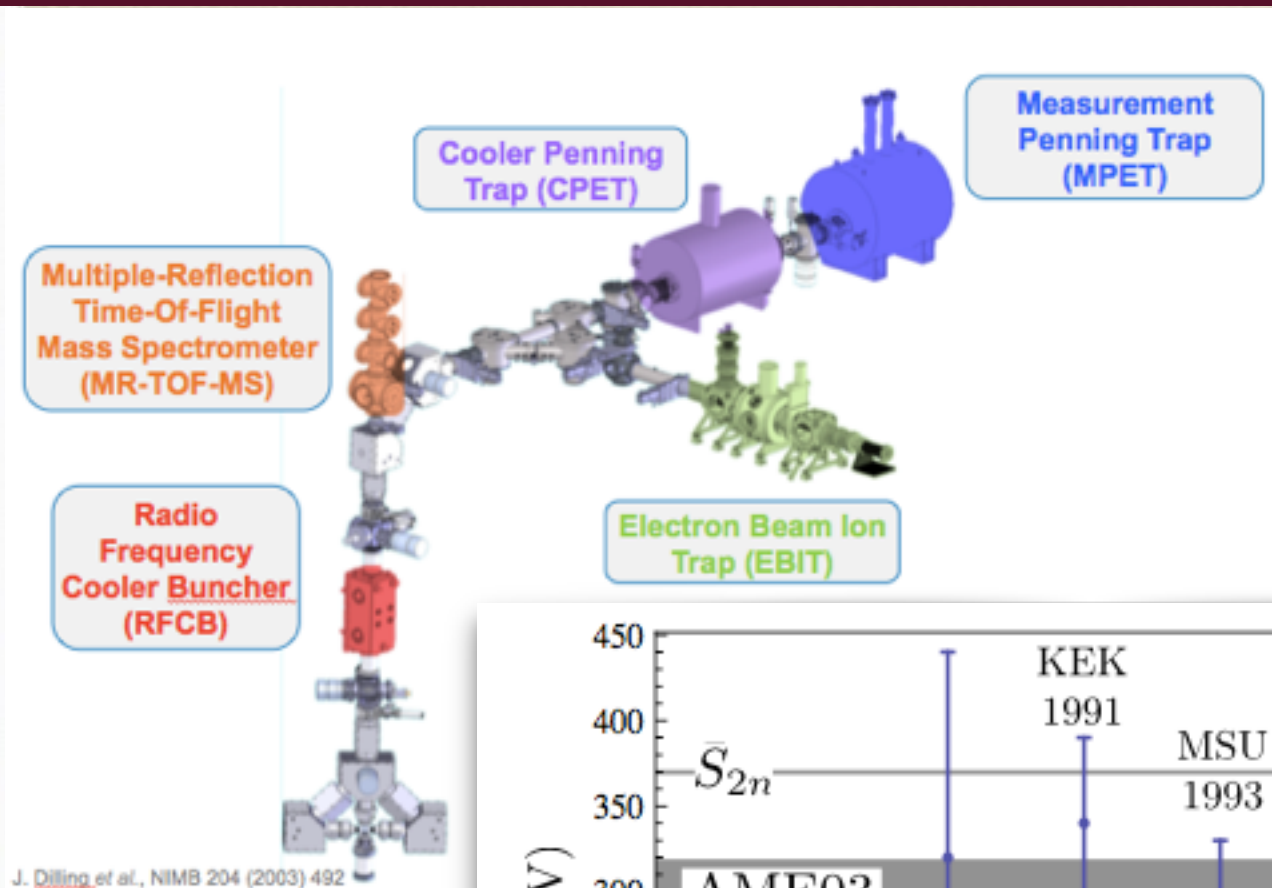

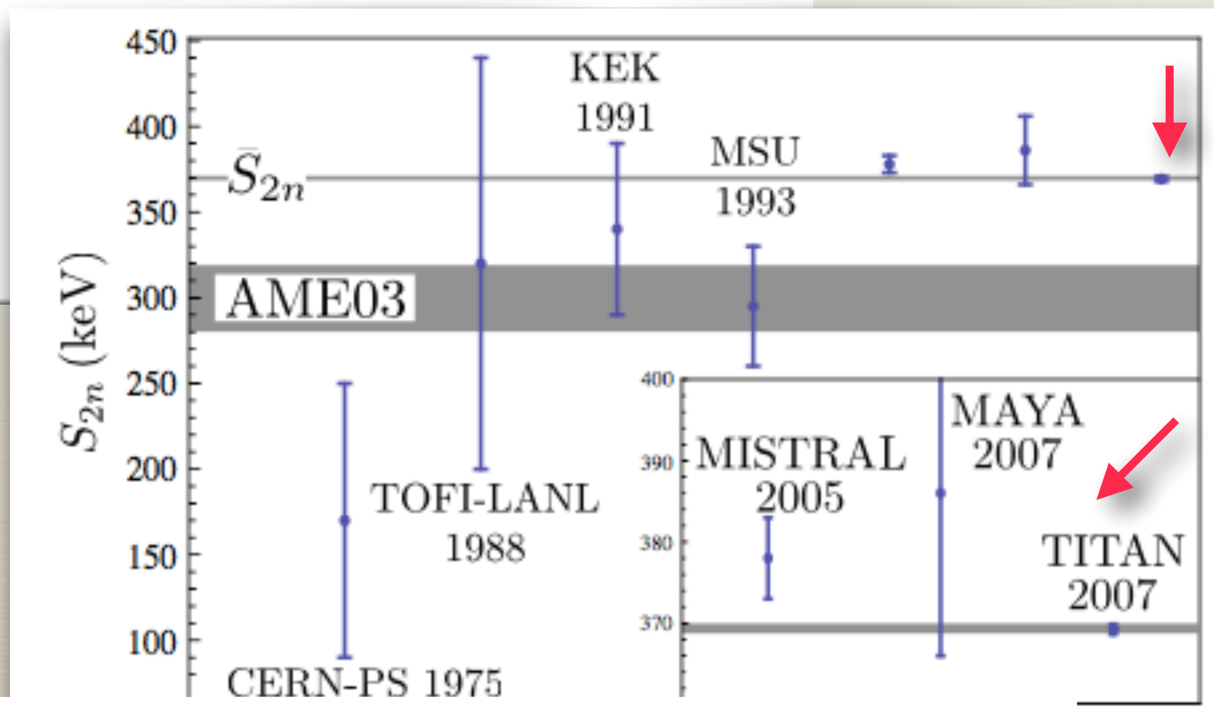

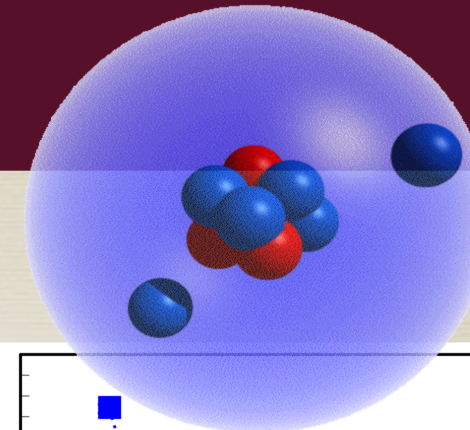

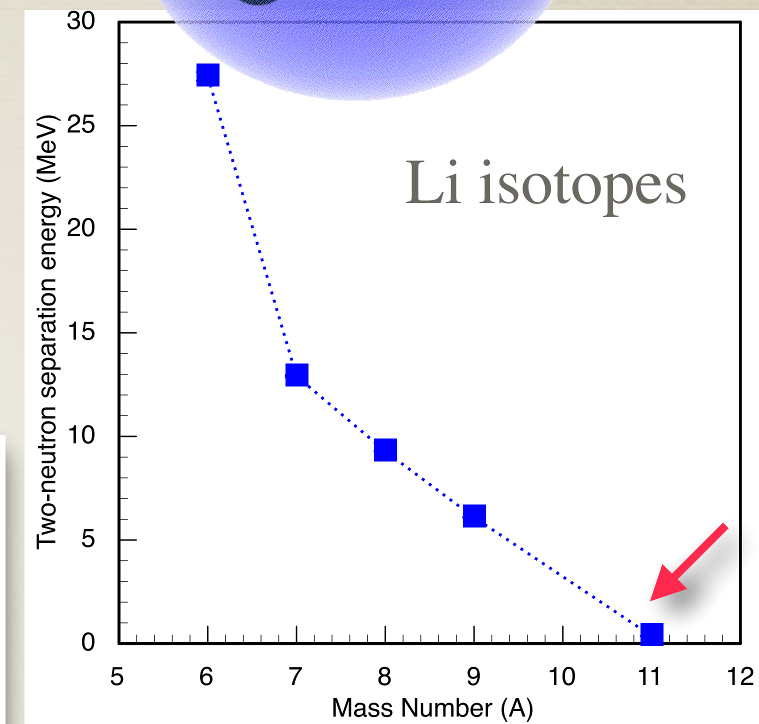

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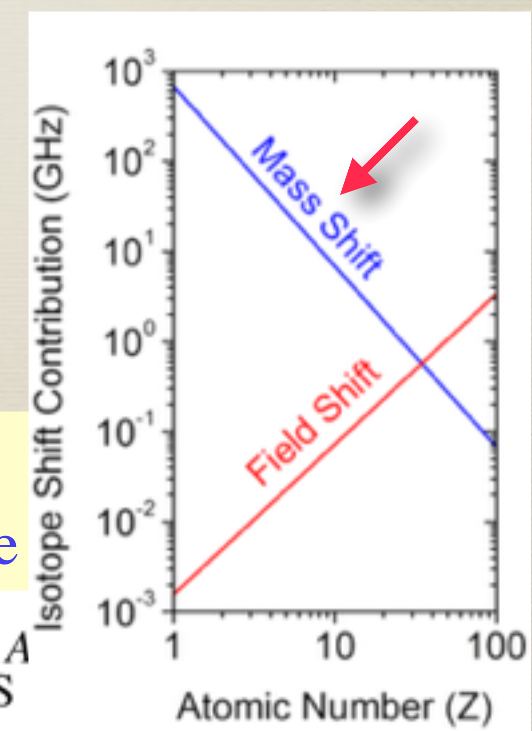
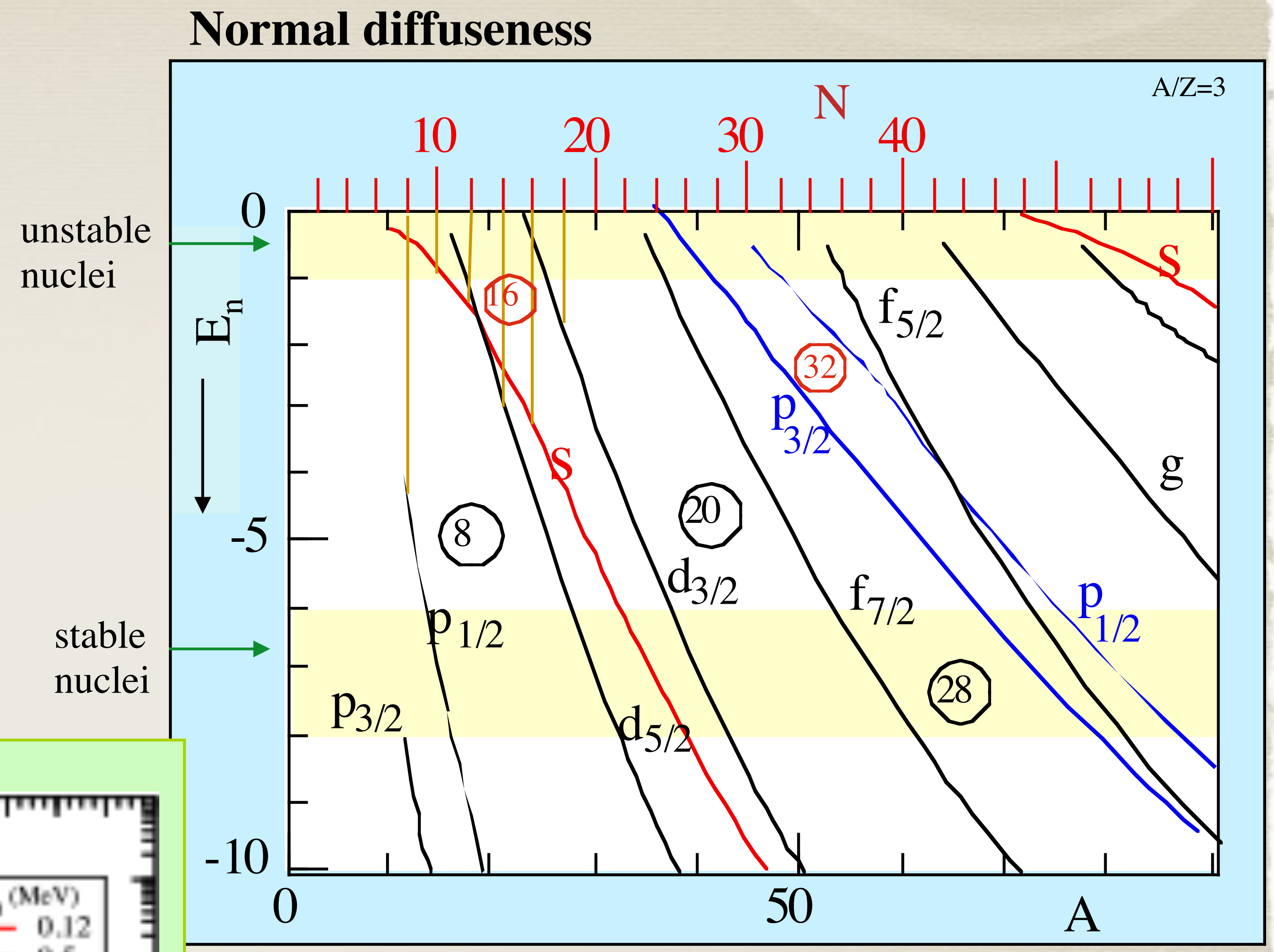
Accurate mass needed for isotope shift measuring charge radii

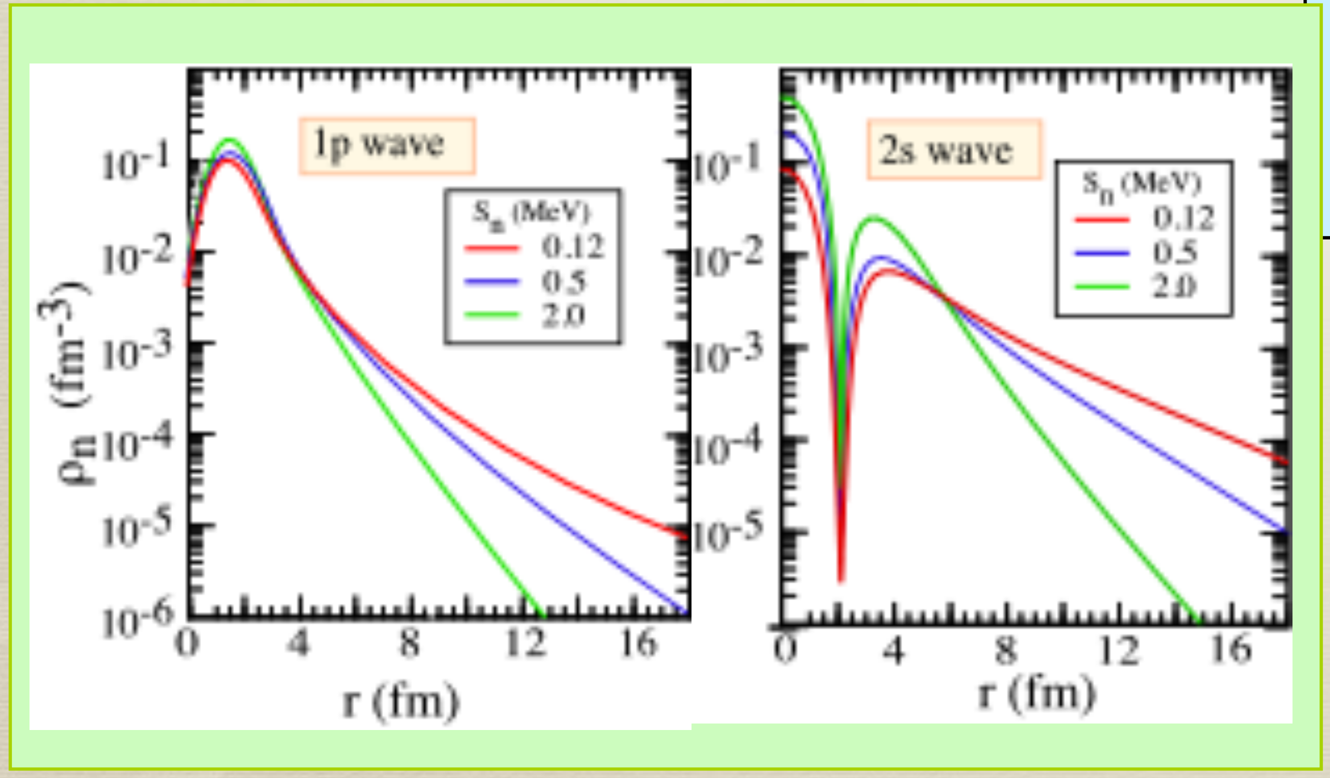
$$\delta\nu_{IS}^{AA'} = \delta\nu_{MS}^{AA'} + \delta\nu_{FS}^{AA'}$$

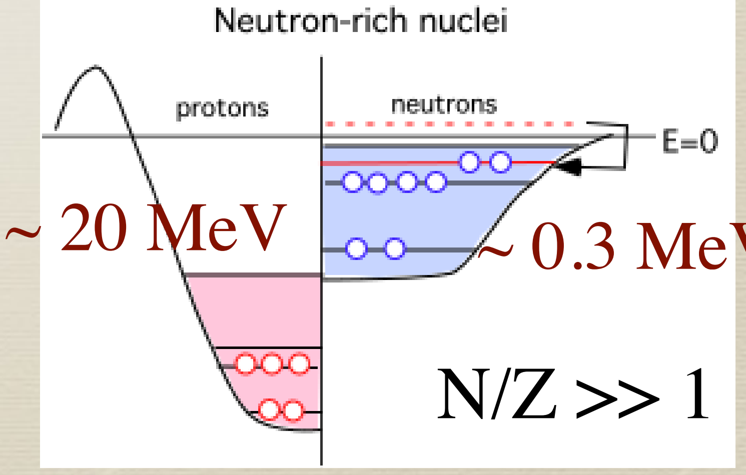


What lies behind the halo

- Small neutron separation energy
- Neutron orbital re-ordering







Defining the Borromean image

PRL 96, 033002 (2006) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 200

Nuclear Charge Radii of ^{9,11}Li: The Influence of Halo Neutrons

Does the halo influence the protons ?

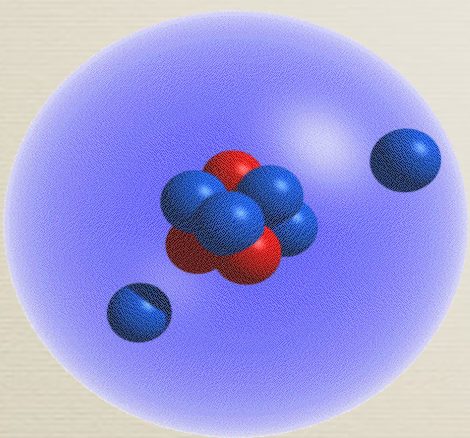
Charge radius

@ TRIUMF

Isotope Shift

$$\delta\nu_{\mathrm{IS}}^{AA'} = \delta\nu_{\mathrm{MS}}^{AA'} + F\,\delta\langle r_{\mathrm{c}}^{2}\rangle^{AA'}$$

R. Sanchez et al, PRL 96(2006)033002



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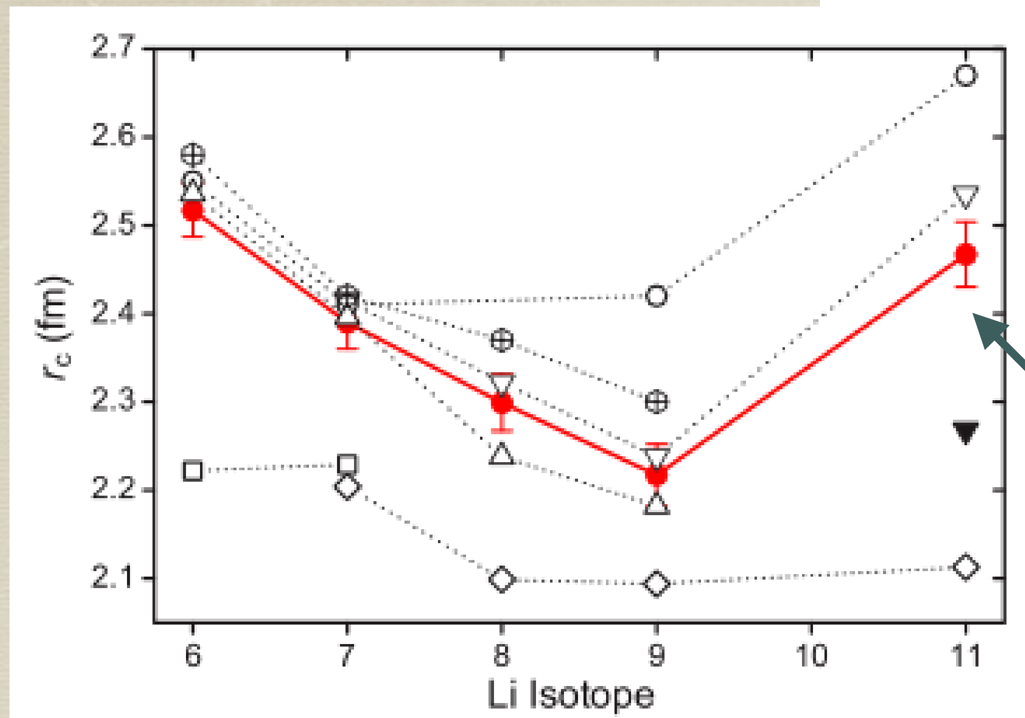

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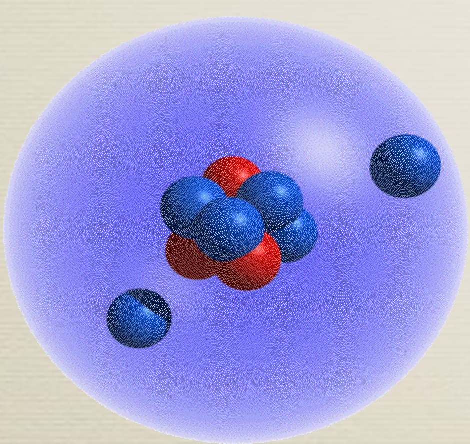
Halo neutrons pull out protons



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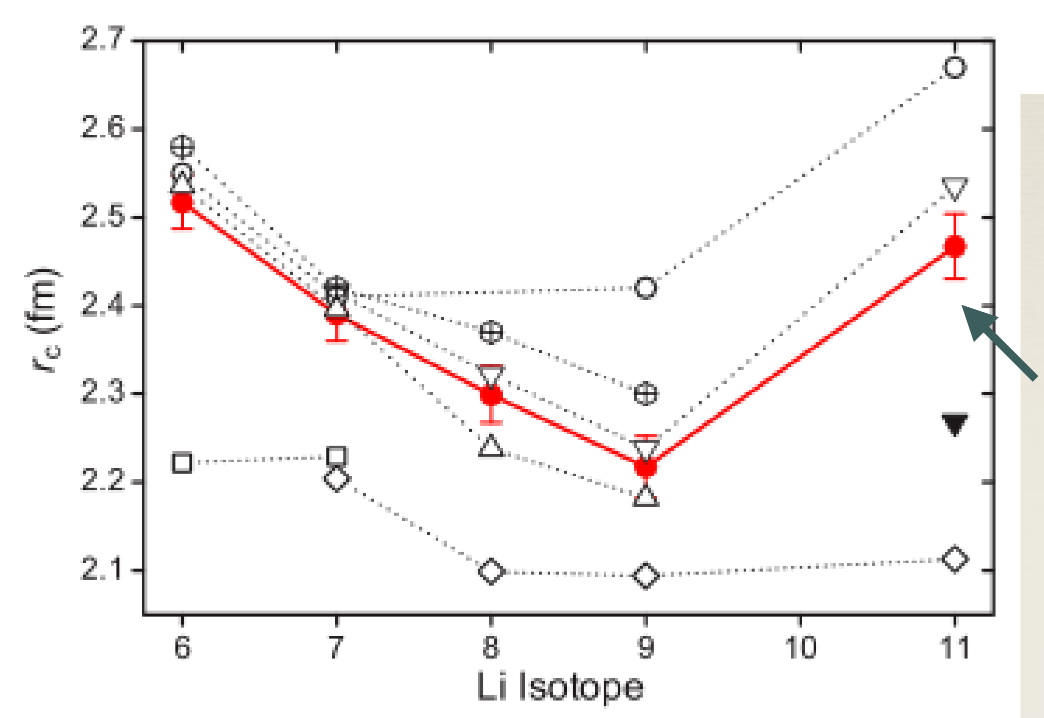

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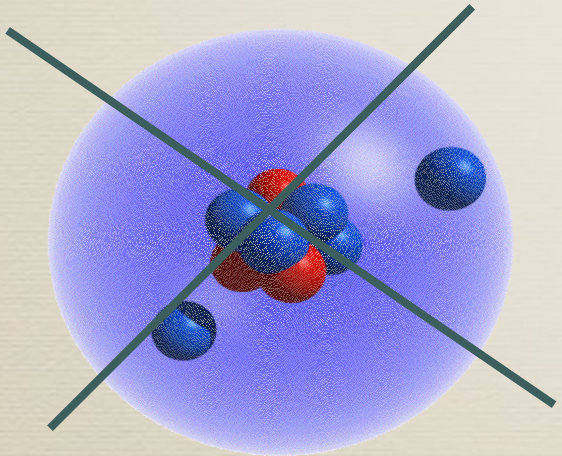
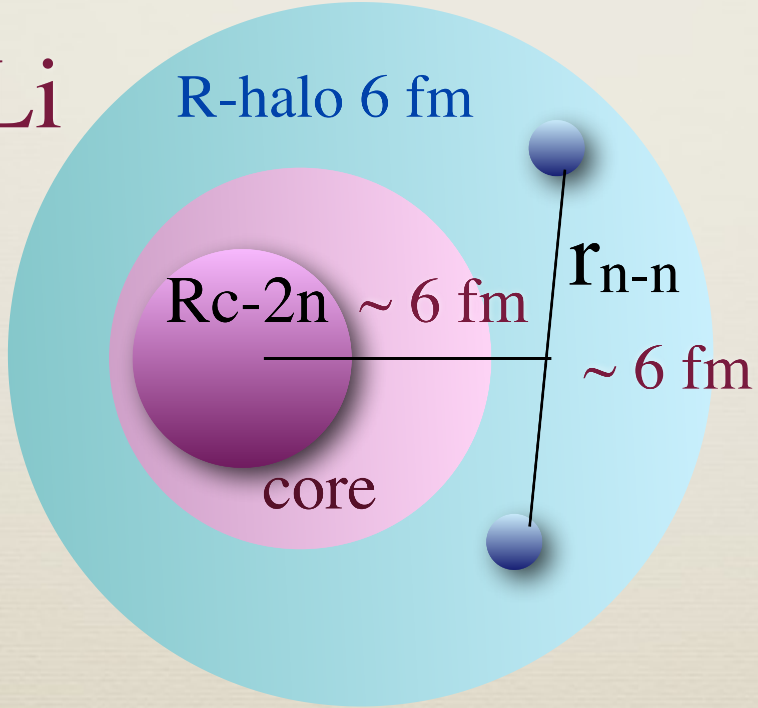


^{11}Li



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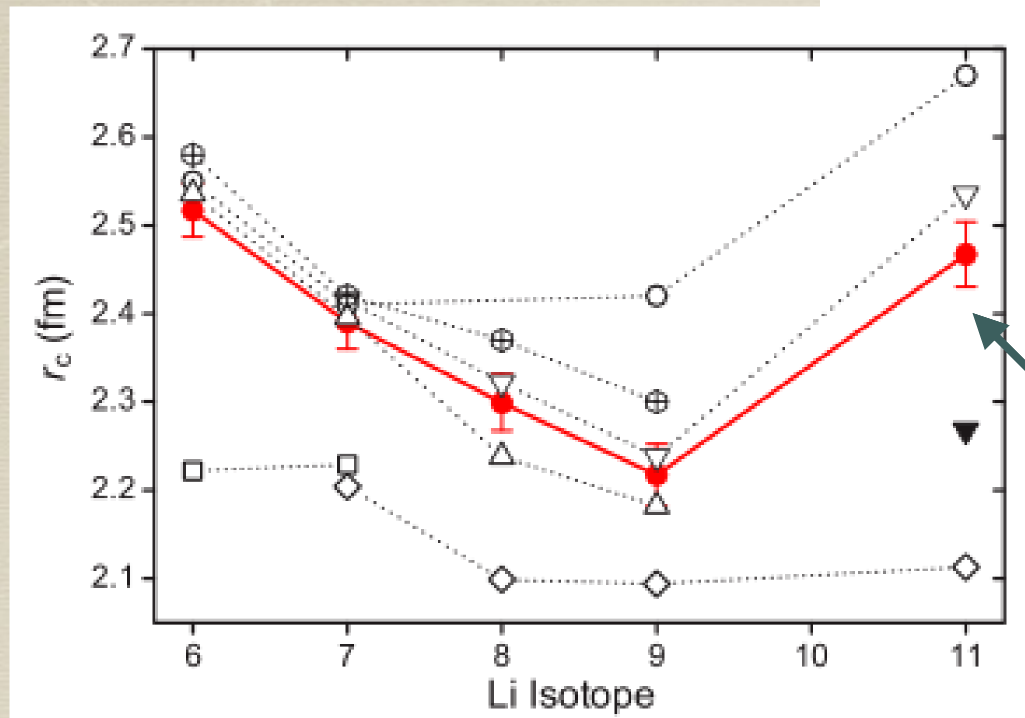

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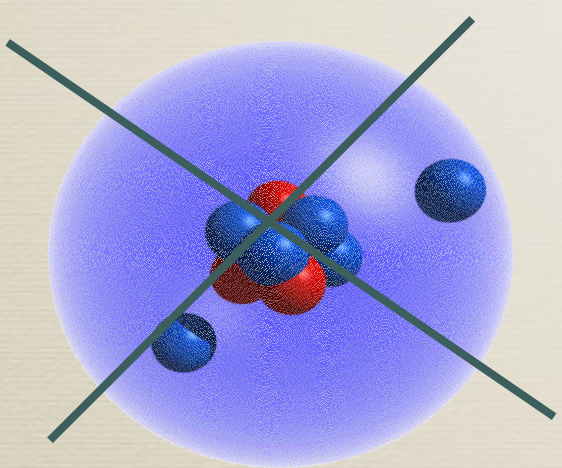
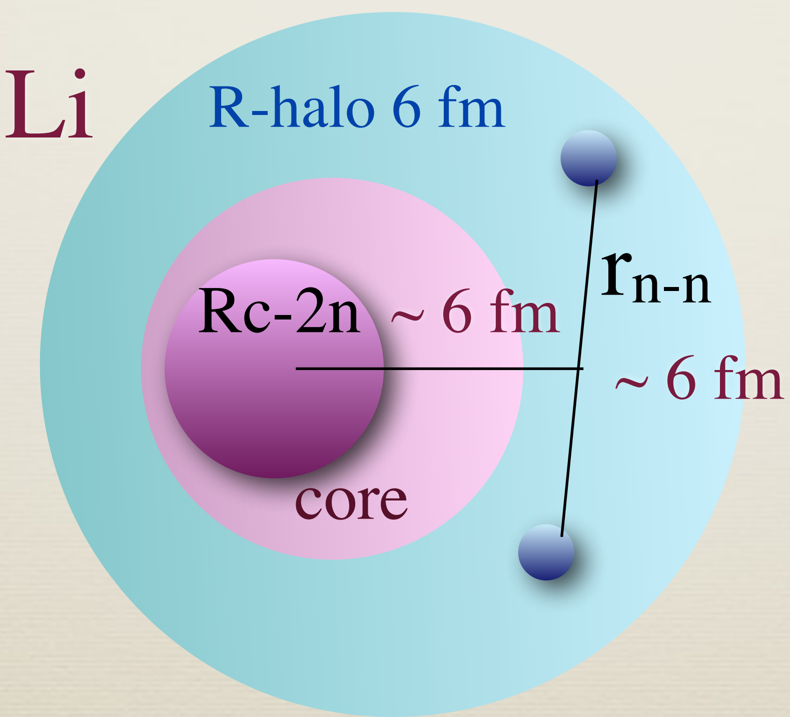
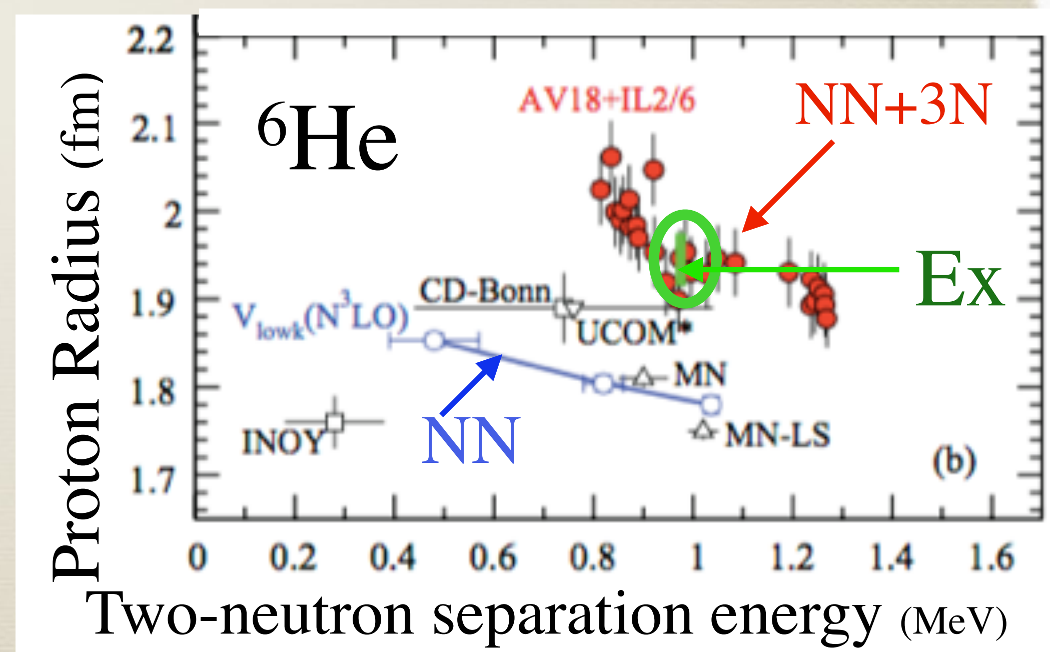






S. Bacca et al. PRC 86 (2012)

Three-nucleon force essential for explaining proton radii

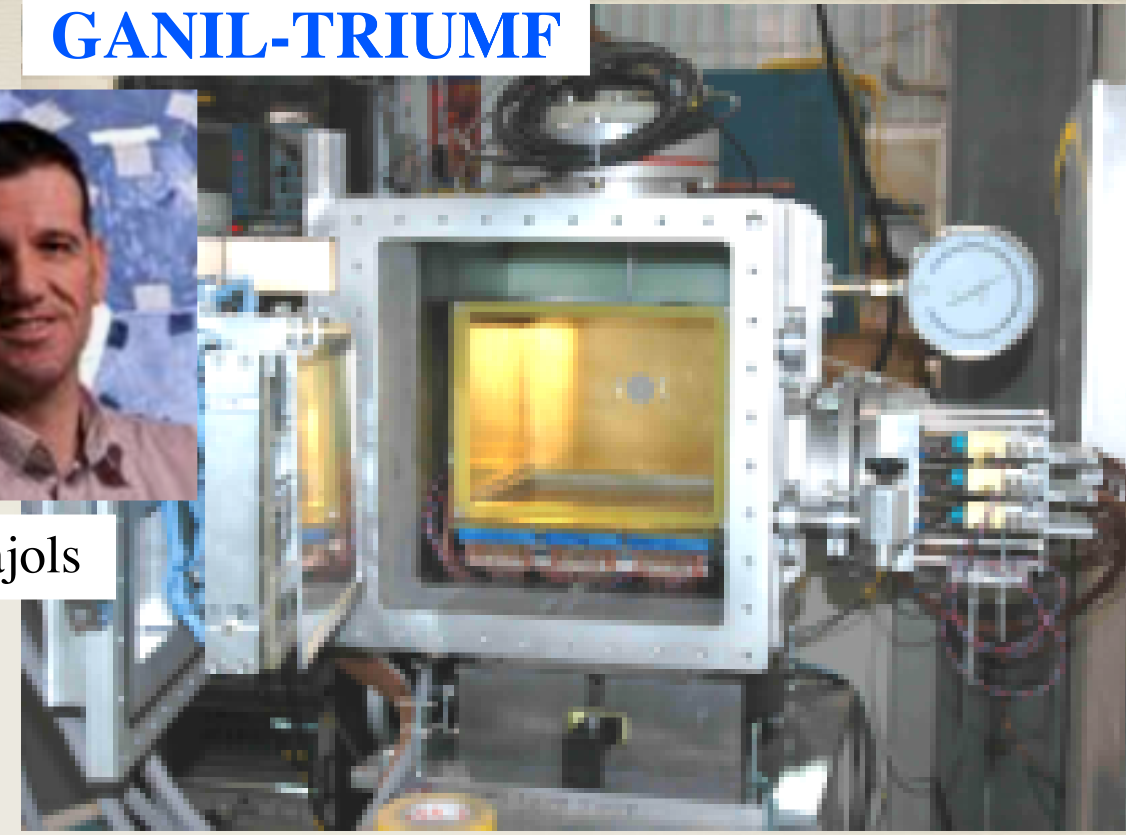
Picking the paired halo neutrons in ^{11}Li

2007

ISAC-II Delivers its first Radioactive Beam to an Experiment.

GANIL-TRIUMF

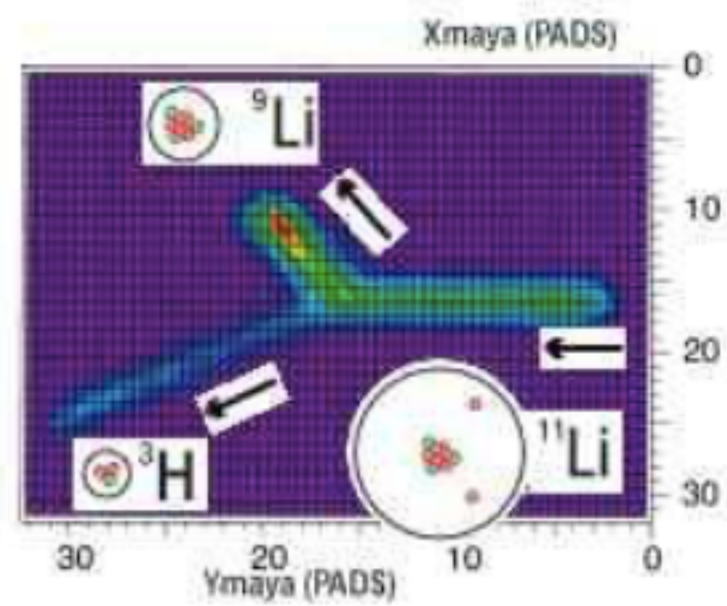
Herve Savajols



Active target Maya from GANIL

^{11}Li(p,t)

ISACII opens new era in halo studies



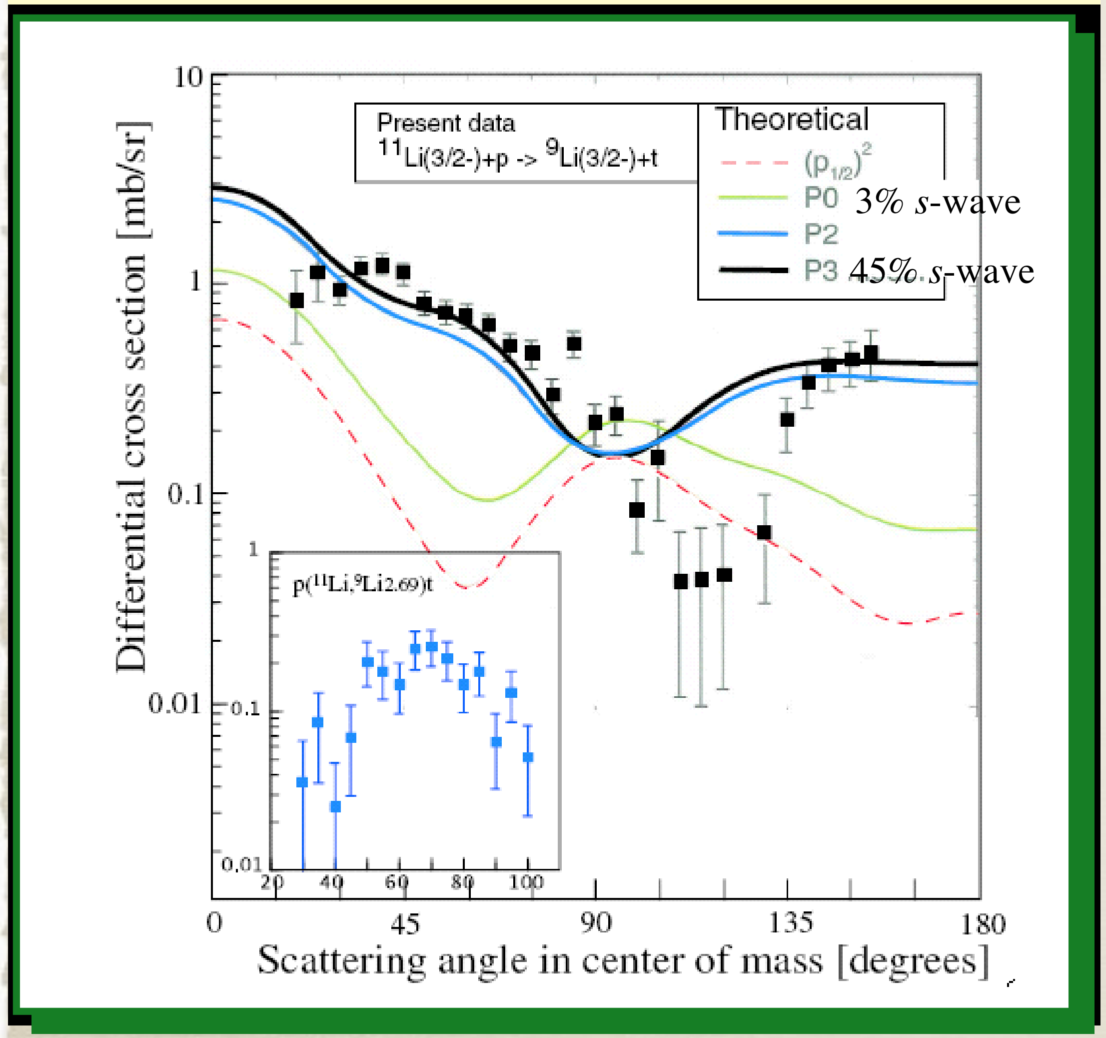
Neutron correlation $^{11}Li+p \longrightarrow {}^{9}Li+t$

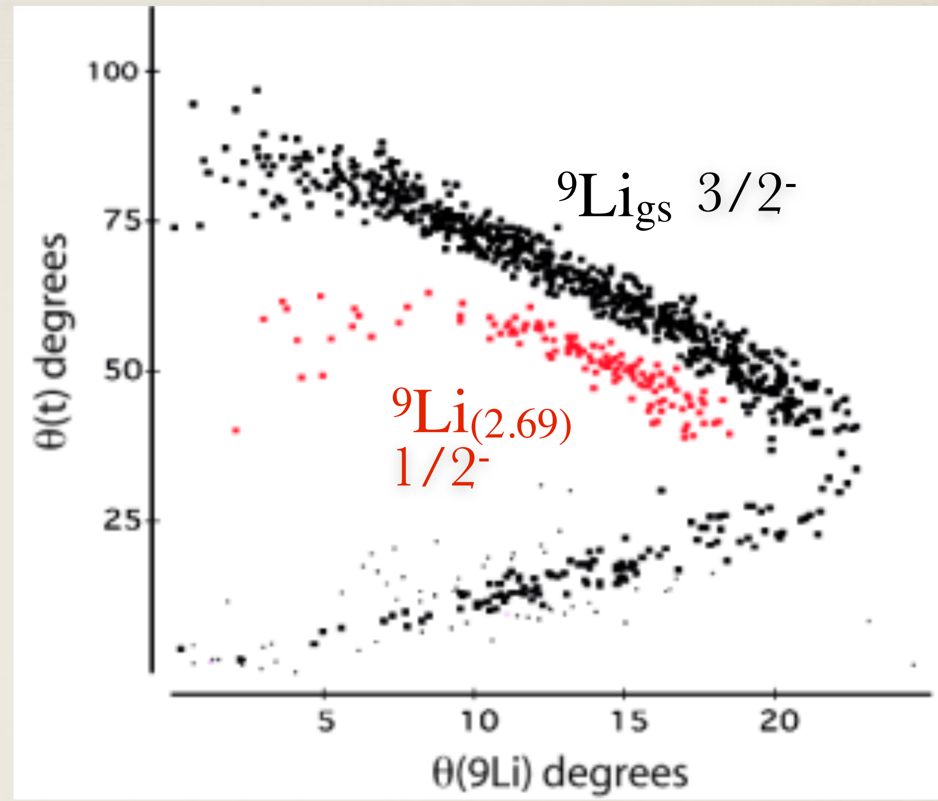
PRL **100,** 192502 (2008) PHYSICAL REVIEW LETTERS week ending 16 MAY 2008

Measurement of the Two-Halo Neutron Transfer Reaction $^{1}H(^{11}Li, {}^{9}Li)^{3}H$ at 3*A* MeV

I. Tanihata et al.

Correlated *n-n* explains data





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$^{11}Li = {}^{9}Li + n + n$

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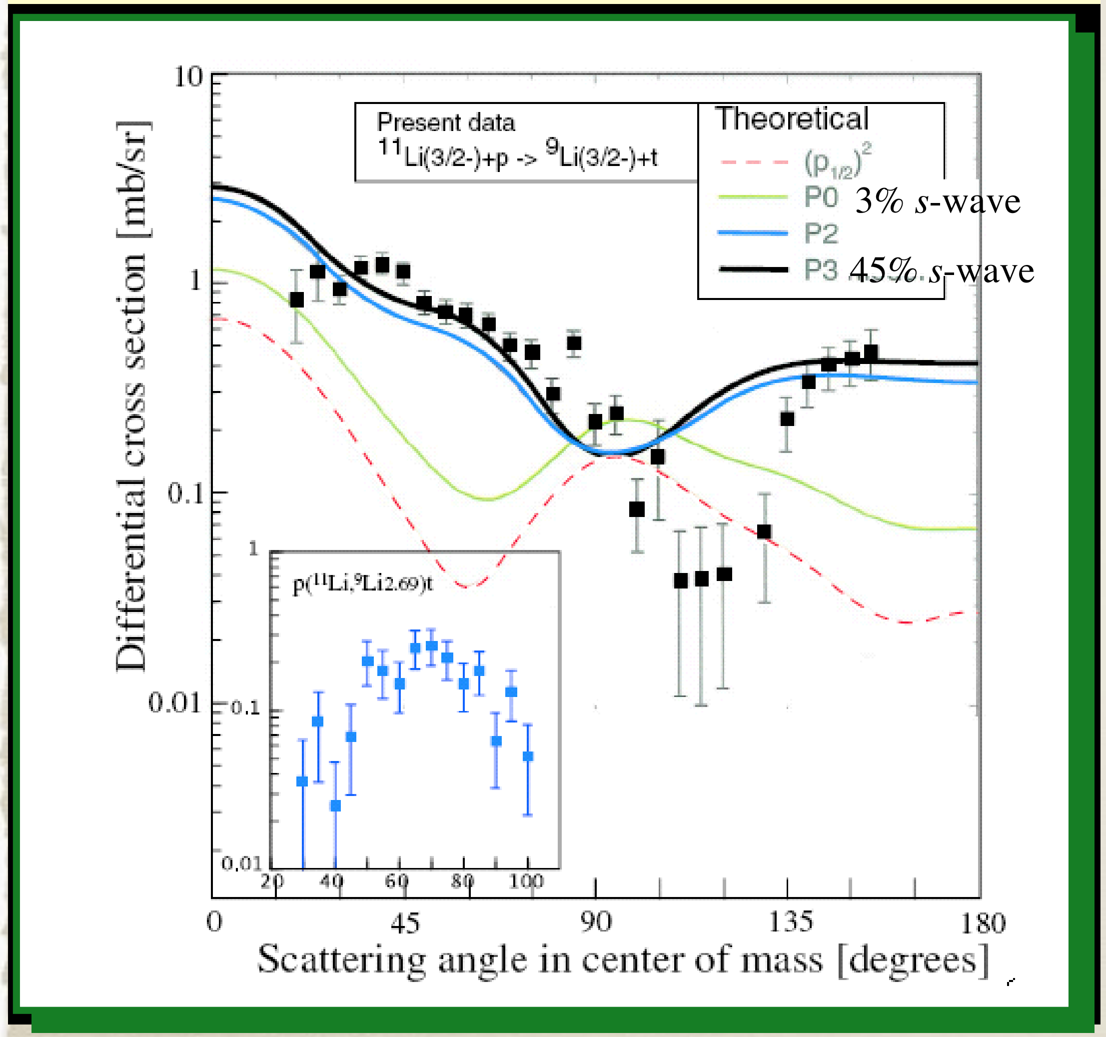

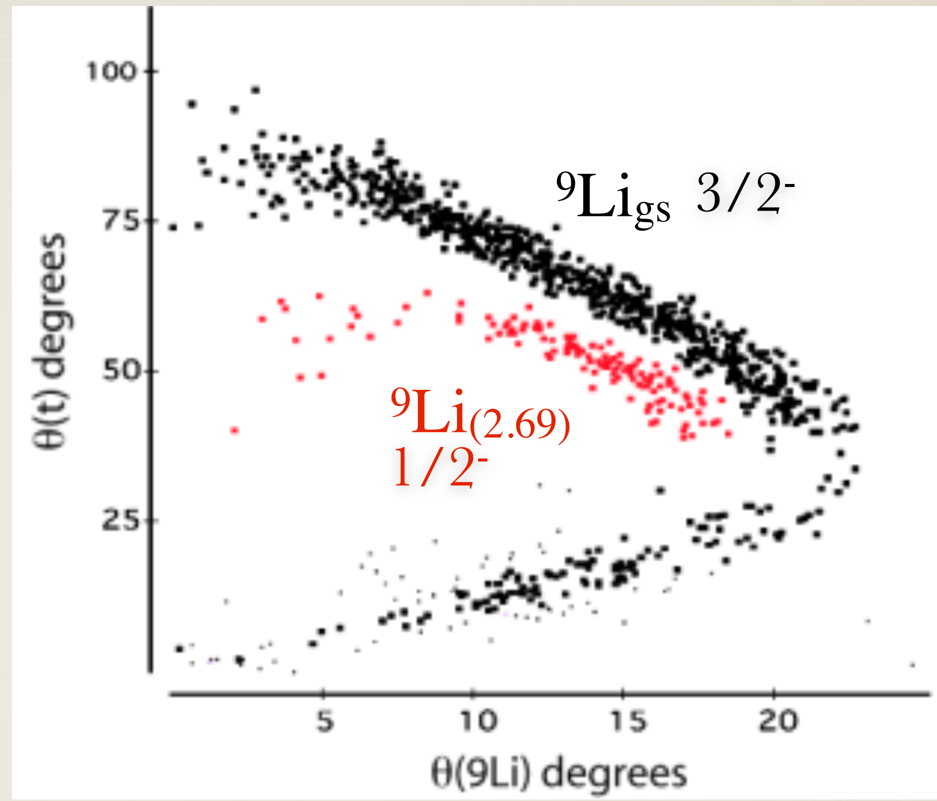

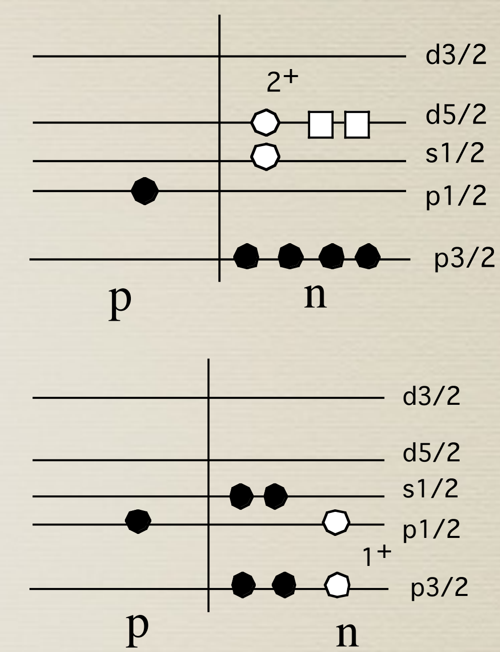

Core (^{9}Li) excited state : $J^{\pi}(n\text{-}n) = 2^+, 1^+$

Evidence of phonon mediated pairing

Exchange of *core-halo* vibration binds the halo

G. Potel et al., Phys. Rev. Lett. 105 (2010) 172502.

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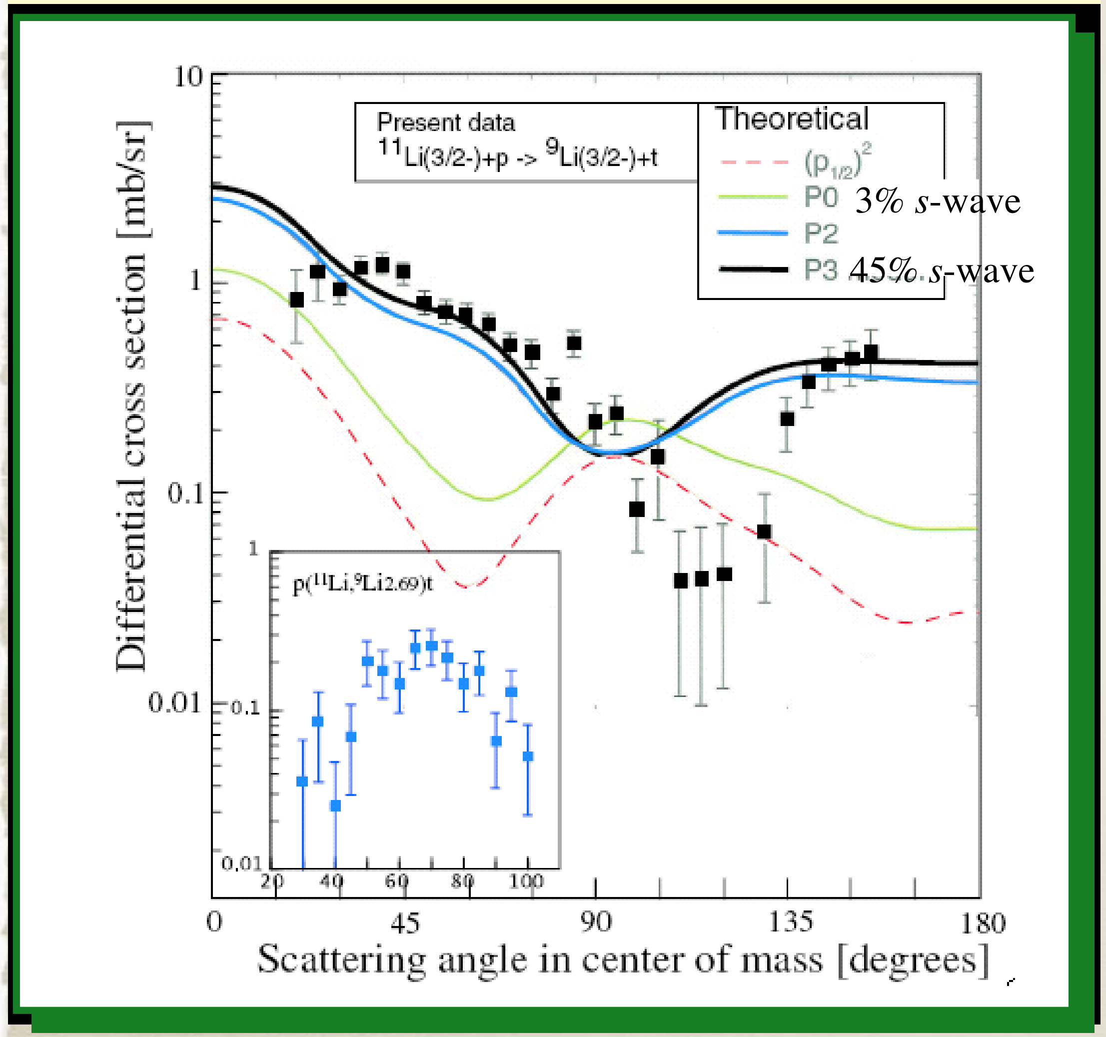
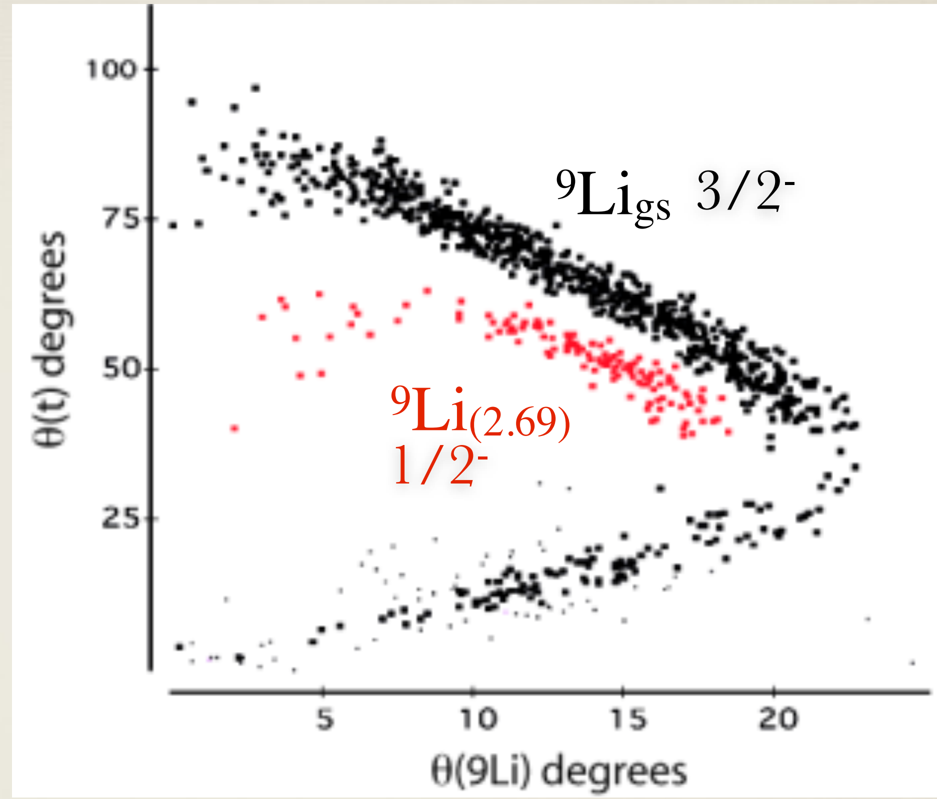
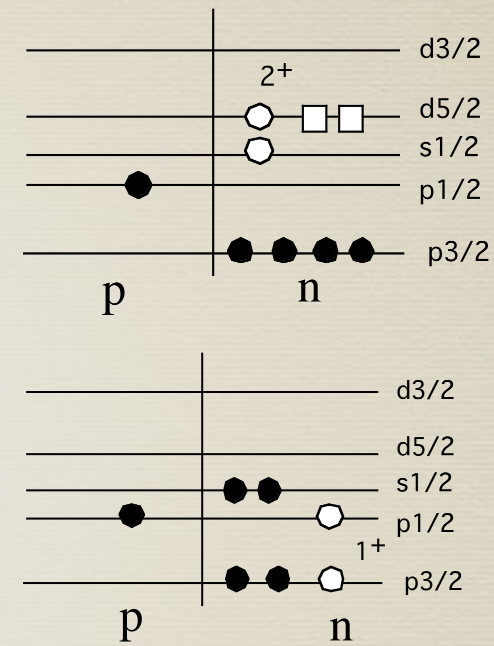




$^{11}Li = {}^{9}Li+n+n$



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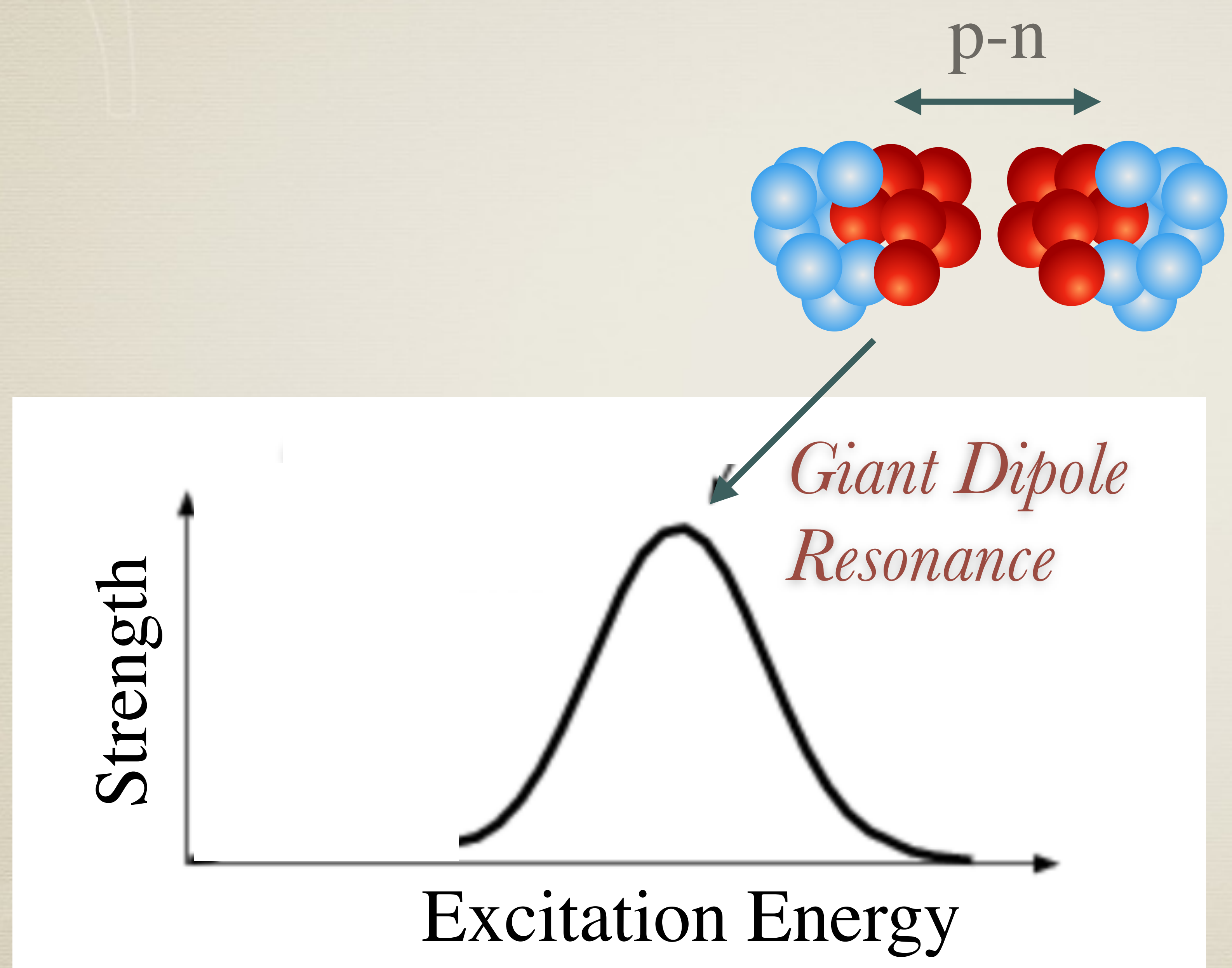
^{9}Li plays a dynamic role in the binding of ^{11}Li

Halo Oscillation : new mode *Soft dipole resonance*



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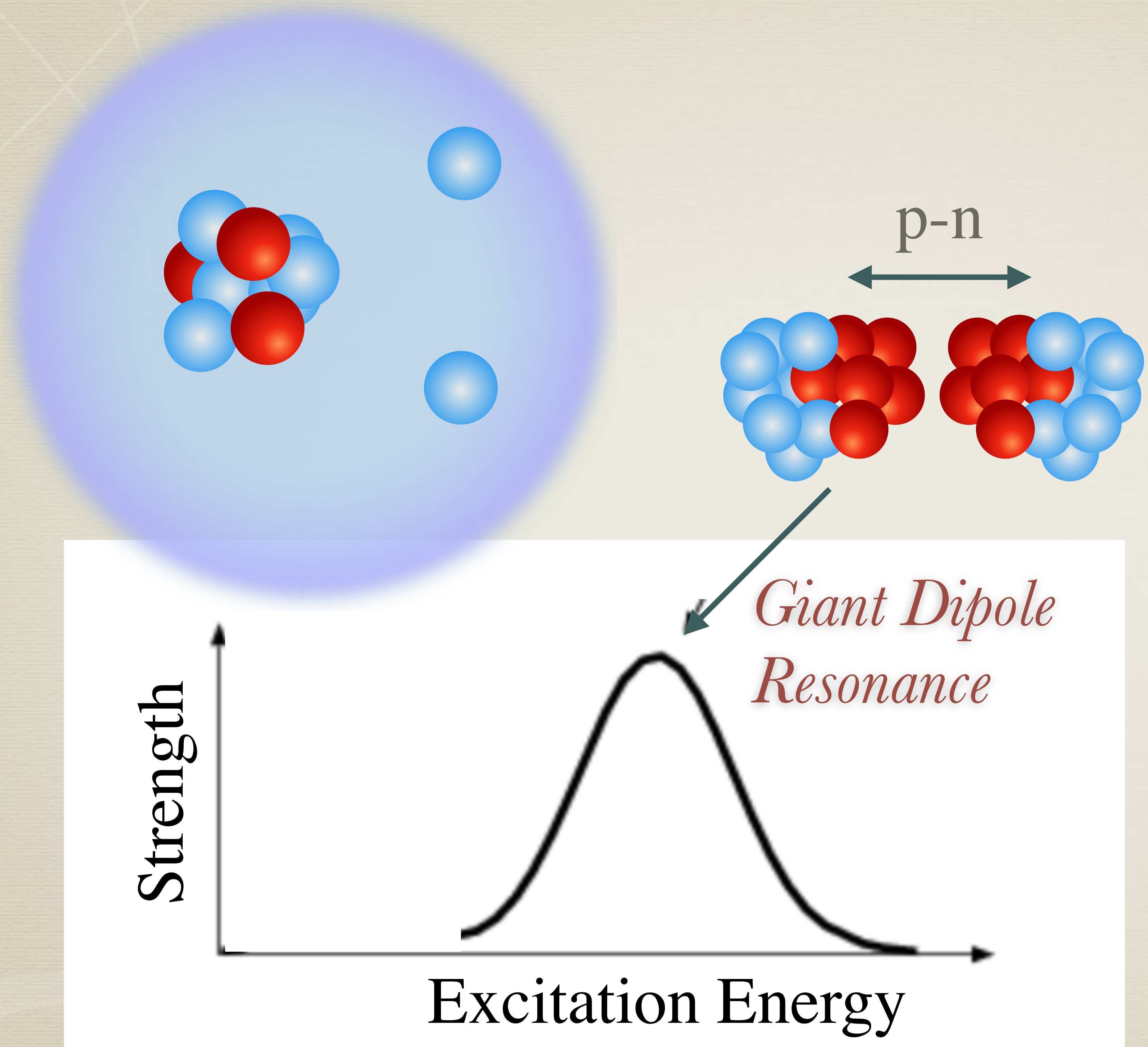

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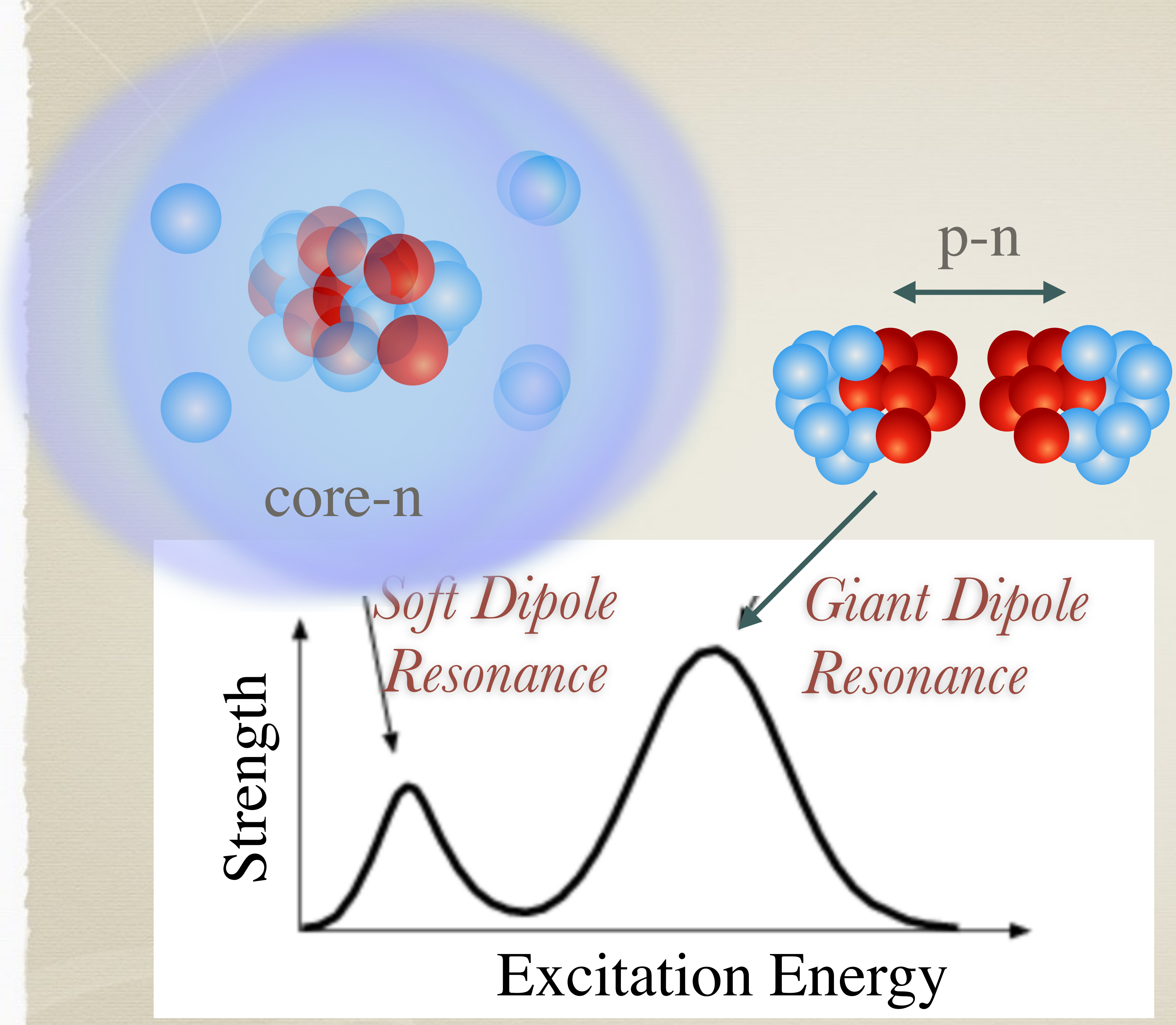

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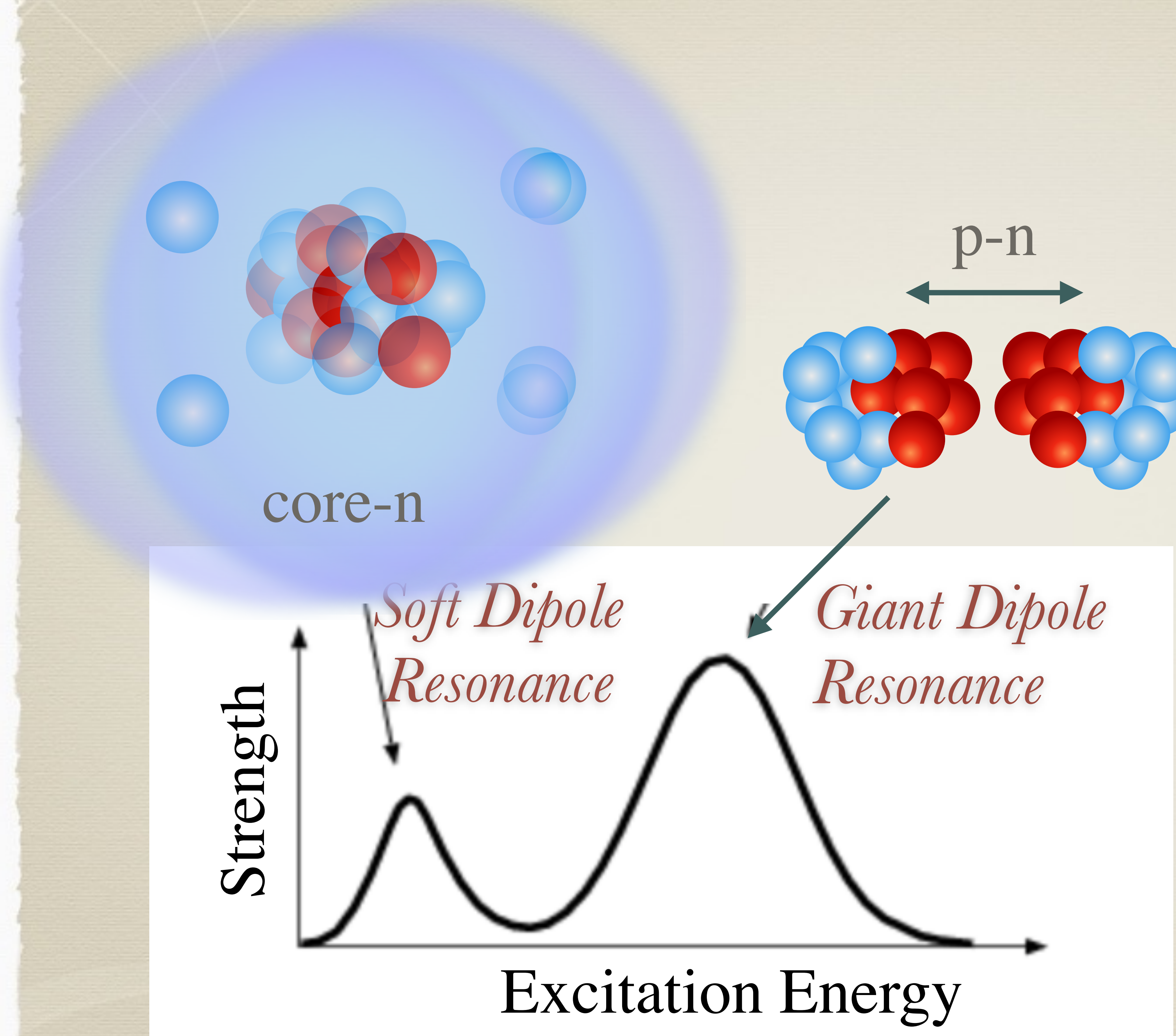
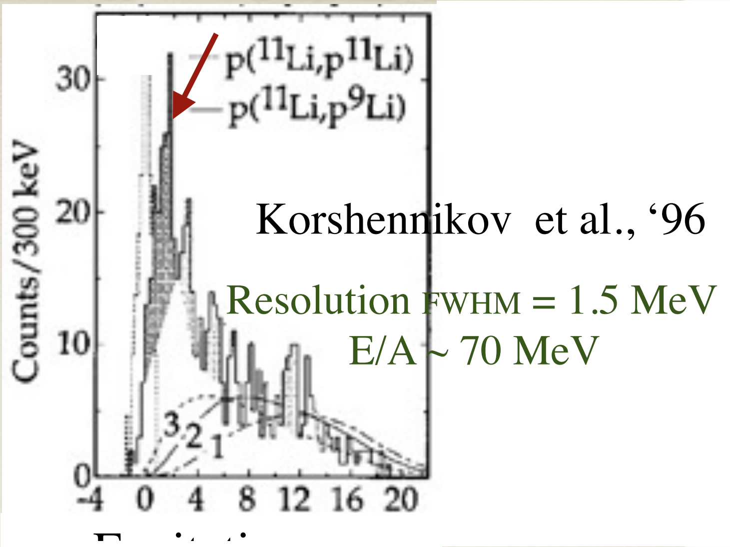
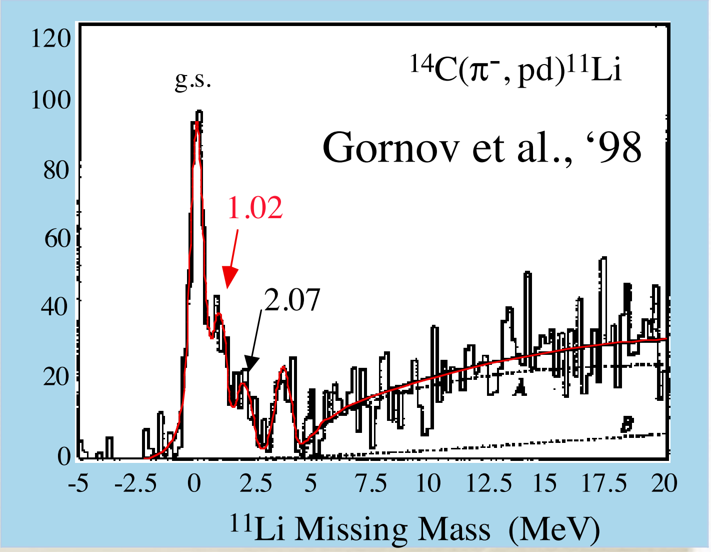
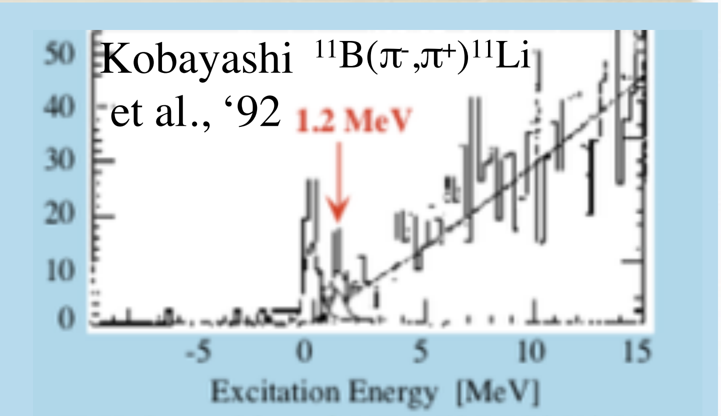


Poor Resolution- resonance not established



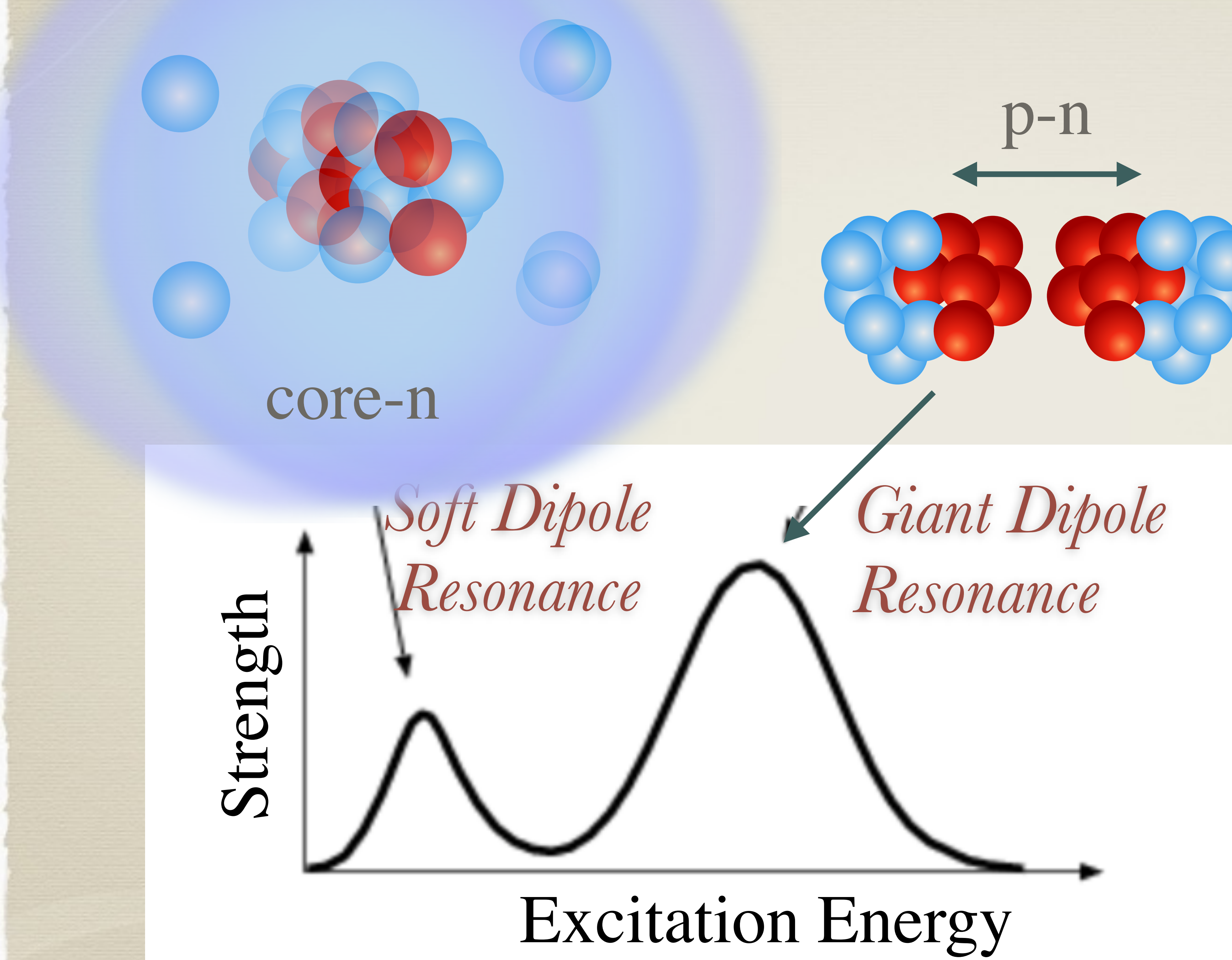
Resonance nature not known





Halo Oscillation : new mode *Soft dipole resonance*

Can the fragile halo sustain a soft dipole resonance ?



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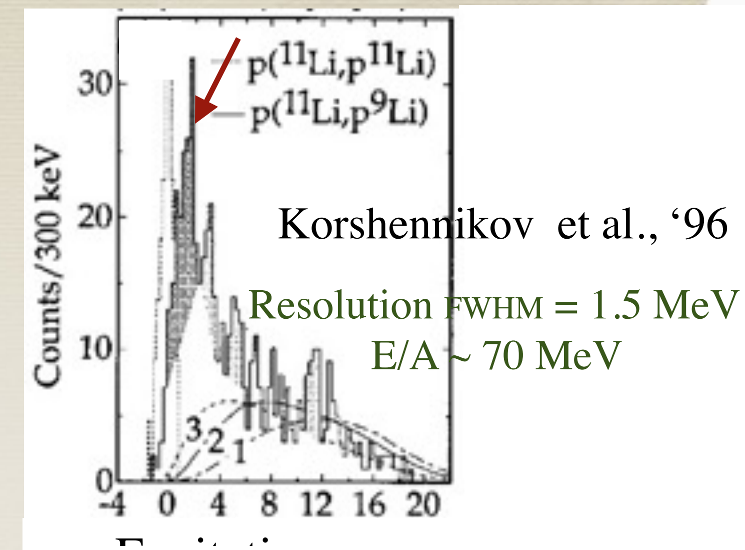

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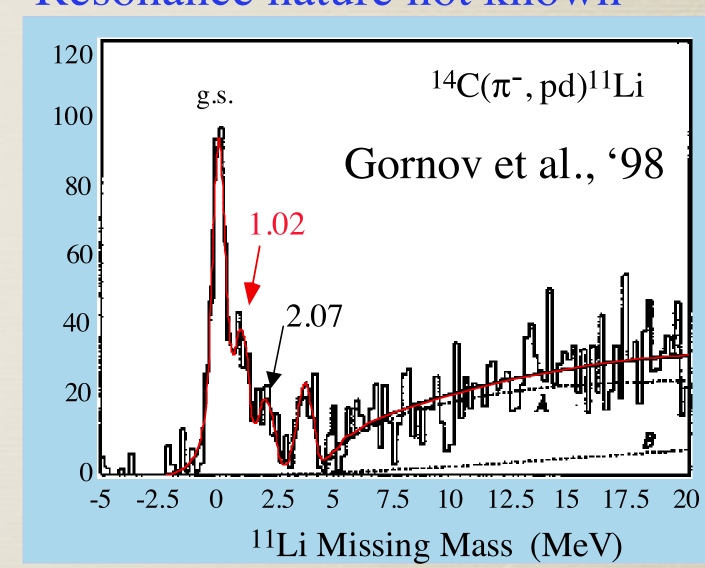
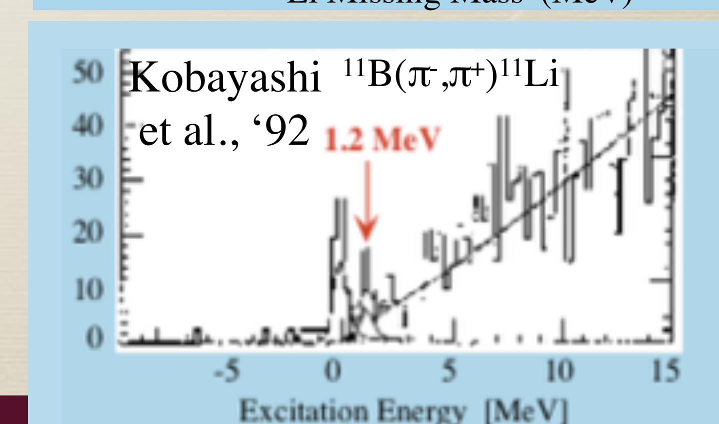
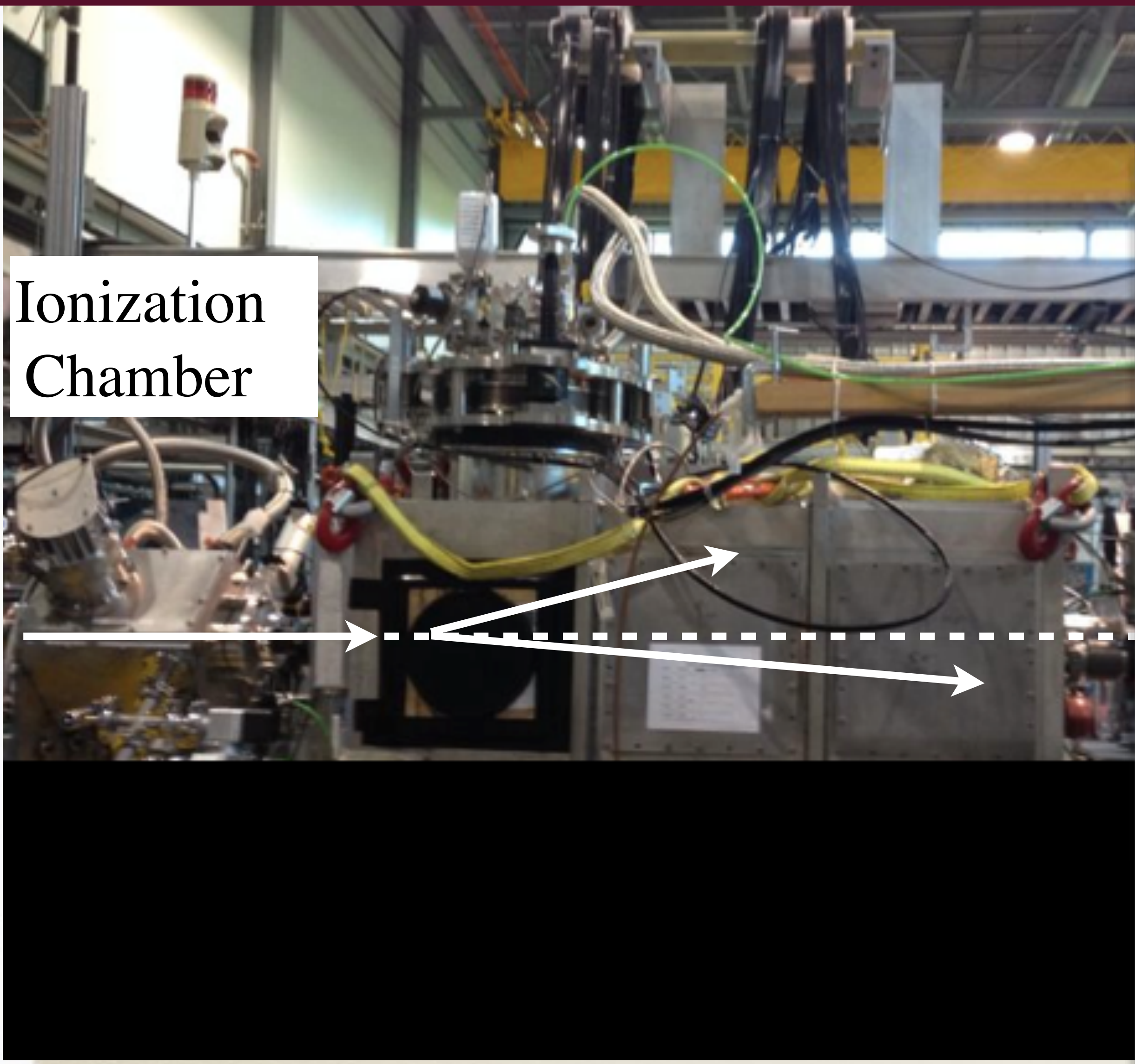
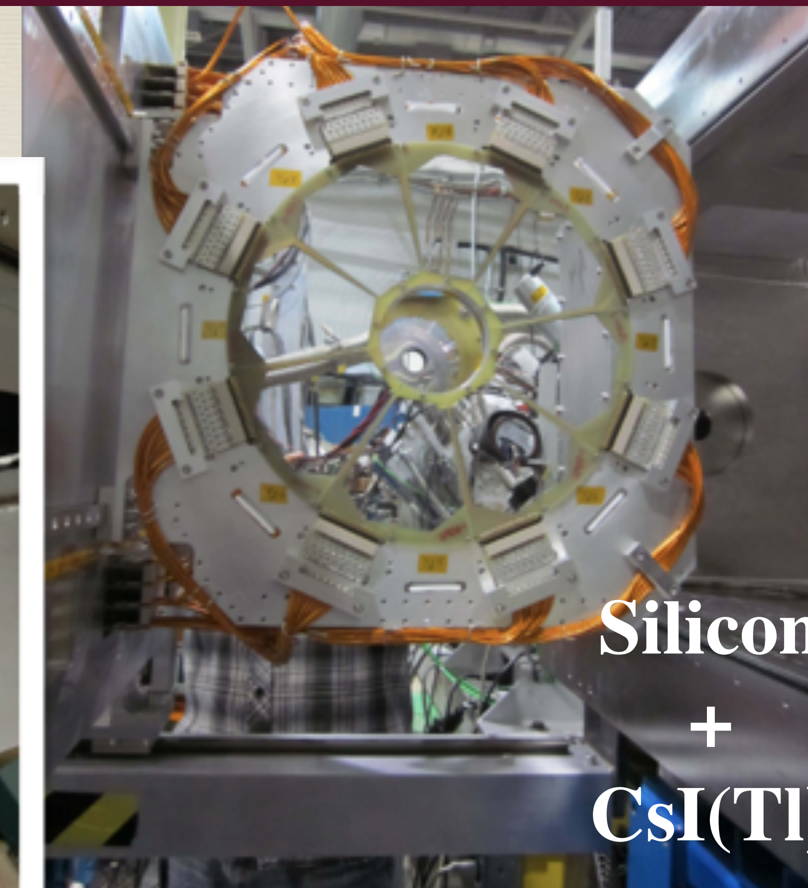




Two decades of various searches did not reach conclusive understanding

IRIS : Reaction spectroscopy station





RCNP KEK
TRIUMF SAINT MARY'S UNIVERSITY SINCE 1802

Unique Feature

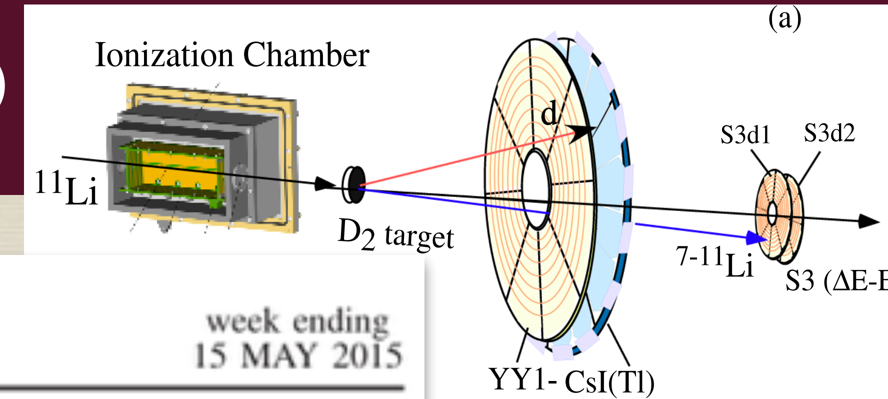
Thin windowless Solid H_2/D_2 target

Higher reaction yield

Negligible background

Exciting ^{11}Li with deuterons

^{11}Li(d,d')



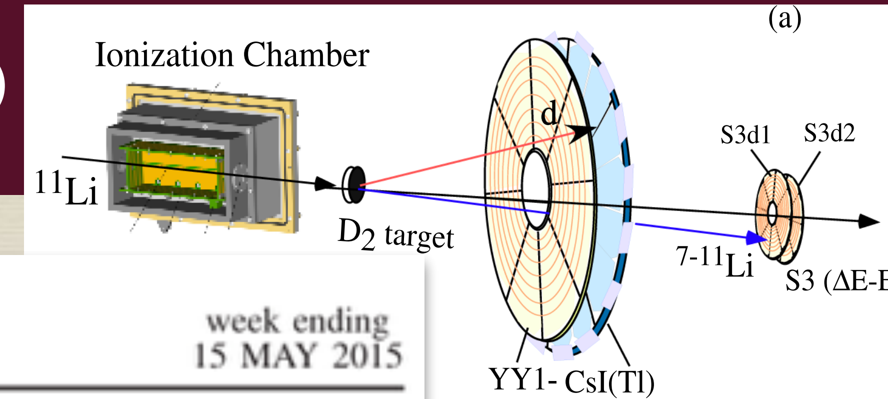
E/A= 5 MeV

PRL **114,** 192502 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

Evidence of Soft Dipole Resonance in ^{11}Li with Isoscalar Character

R.Kanungo, A. Sanetullaev, J. Tanaka et al.

Exciting ^{11}Li with deuterons ^{11}Li(d,d')



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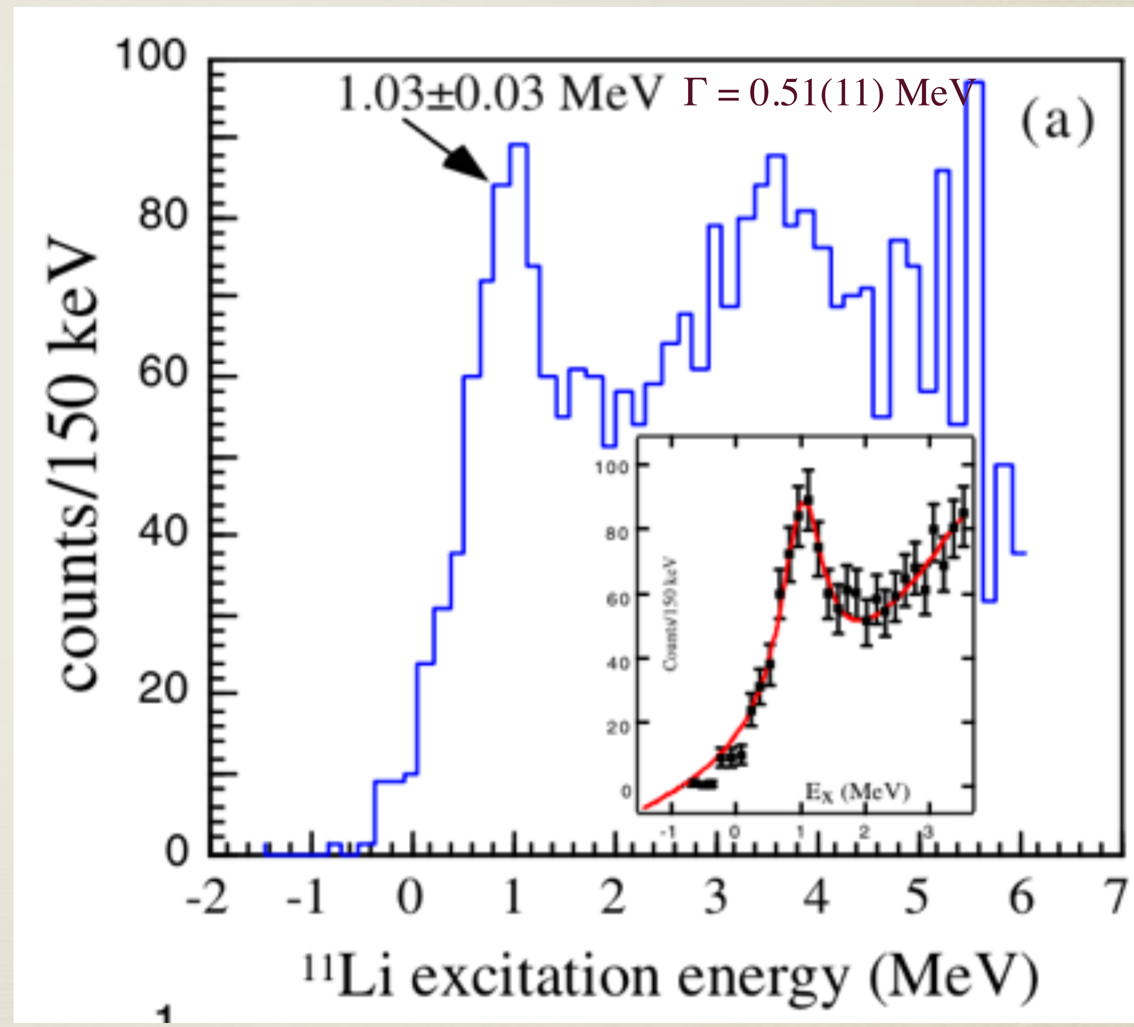

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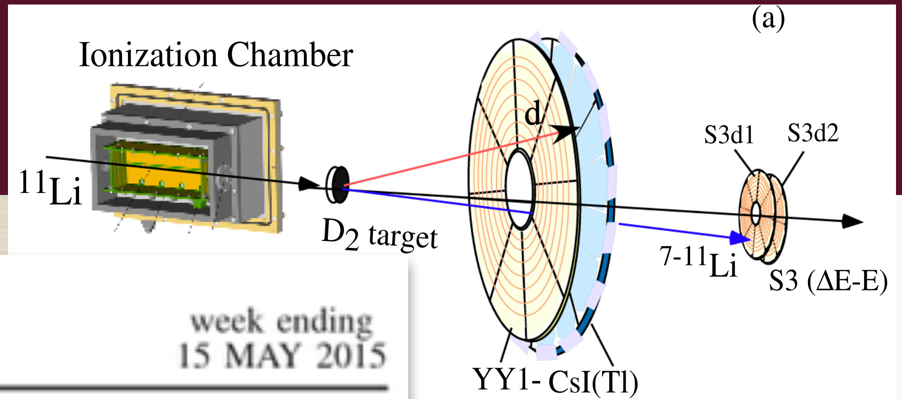

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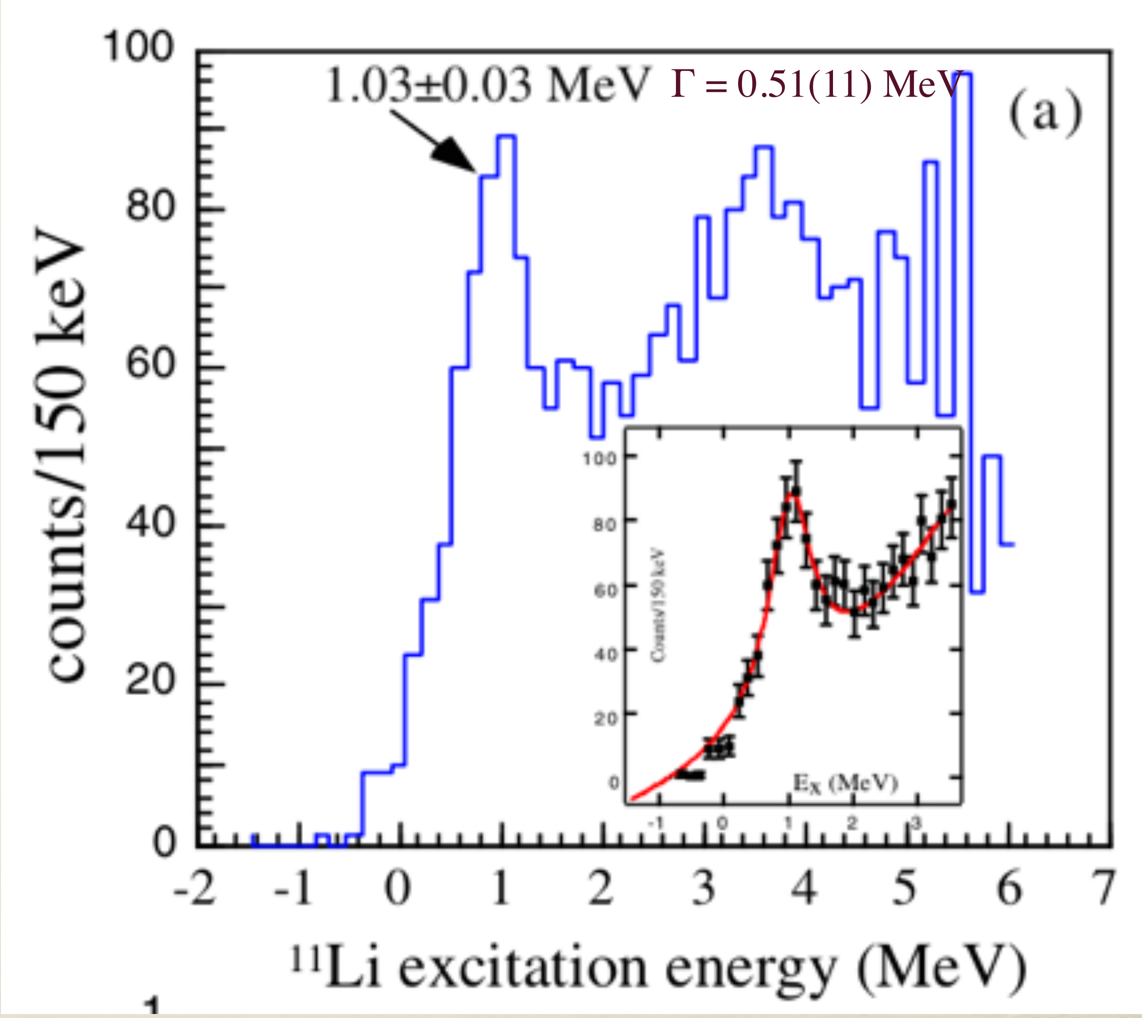
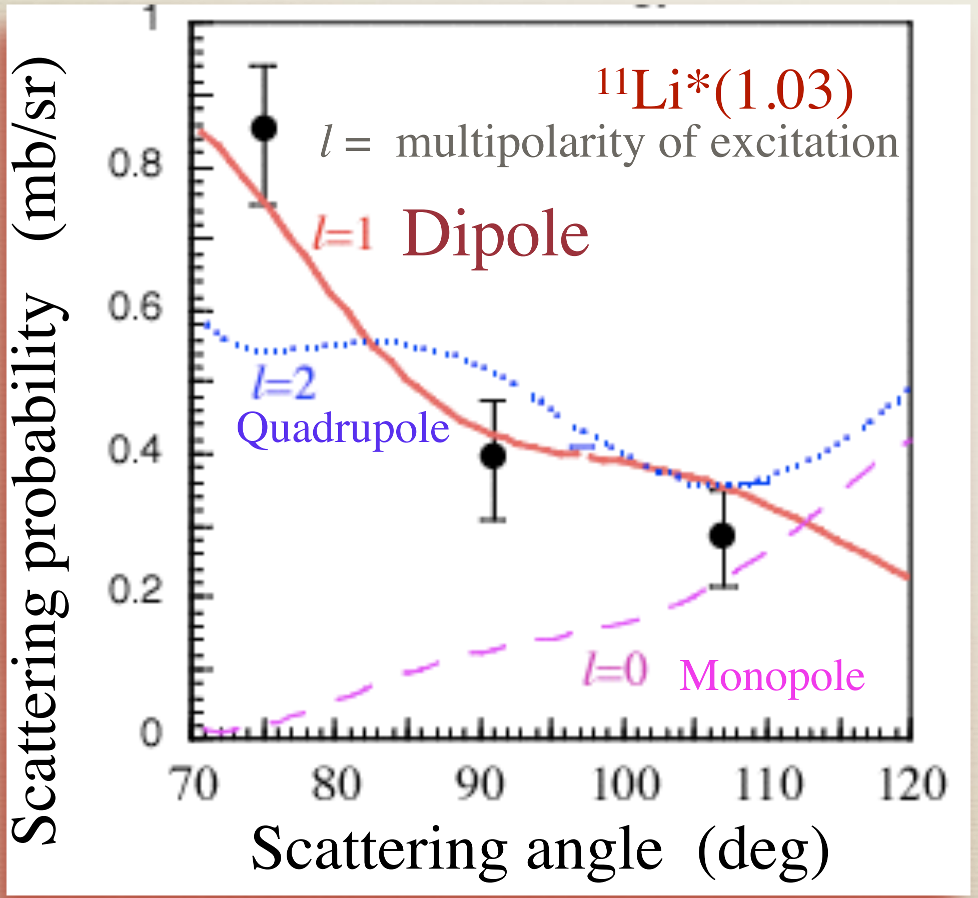




Isoscalar Soft Dipole Resonance Observed

(d,d') $\Delta T=0$

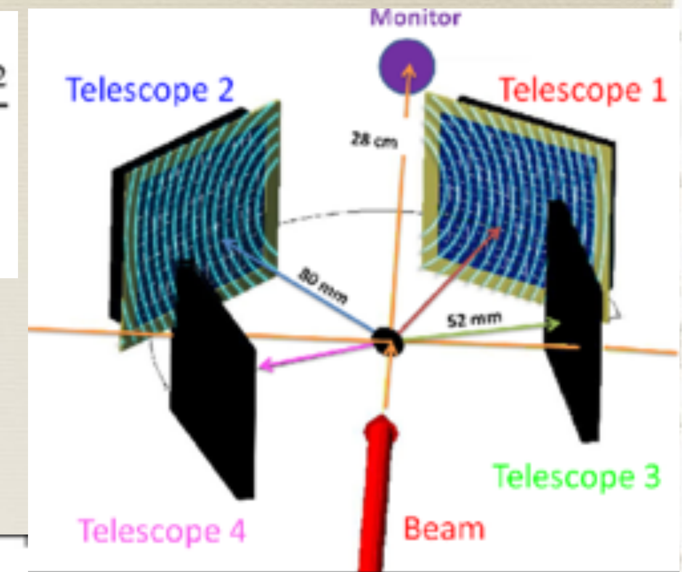
^{11}Li + Pb : Deviating from Rutherford scattering

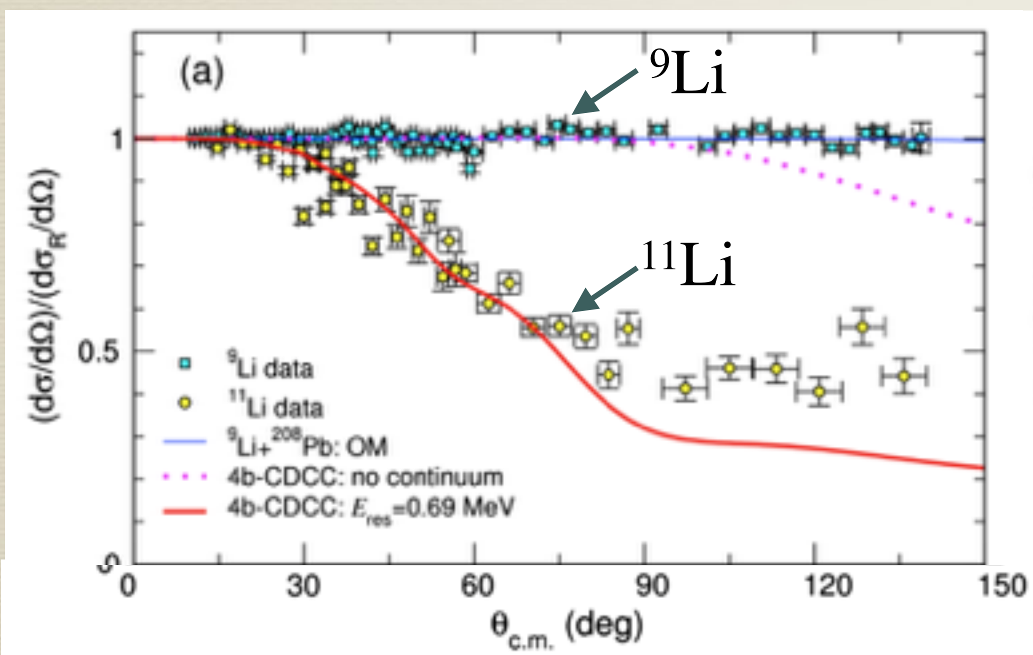
First measurement elastic scattering of ^{11}Li around the Coulomb barrier

PRL **109**, 262701 (2012) PHYSICAL REVIEW LETTERS week ending 28 DECEMBER 2012

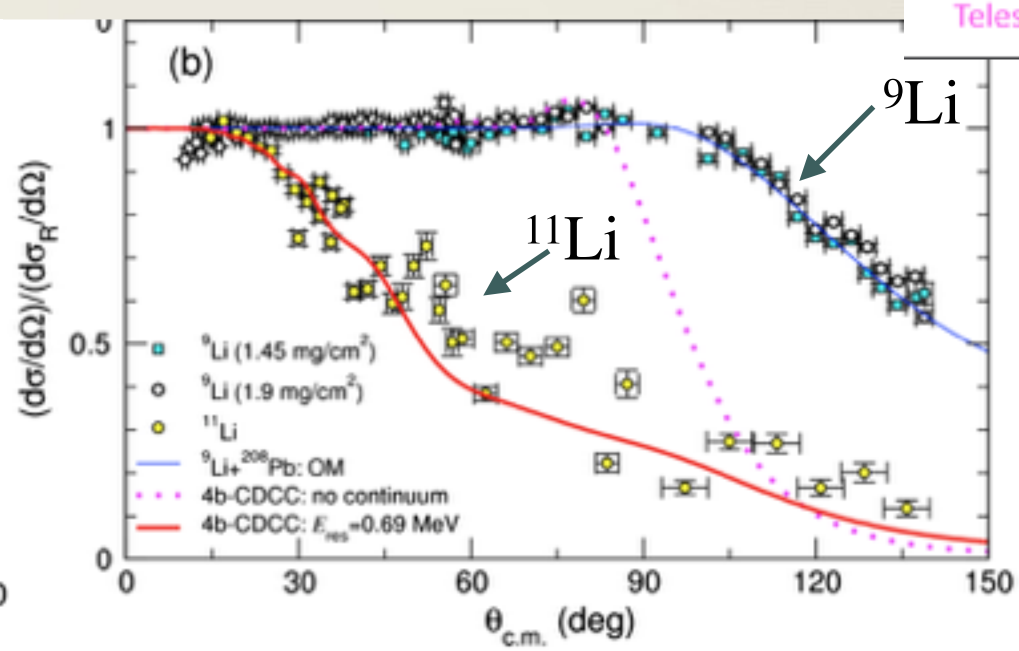
Do Halo Nuclei Follow Rutherford Elastic Scattering at Energies Below the Barrier? The Case of ^{11}Li

M. Cubero et al.,





E_{cm} = 23.1 MeV Below Barrier



E_{cm} = 28.3 MeV Near Barrier

Reduction in dσ/dΩ due to strong dipole coupling between ground state and continuum states in ^{11}Li

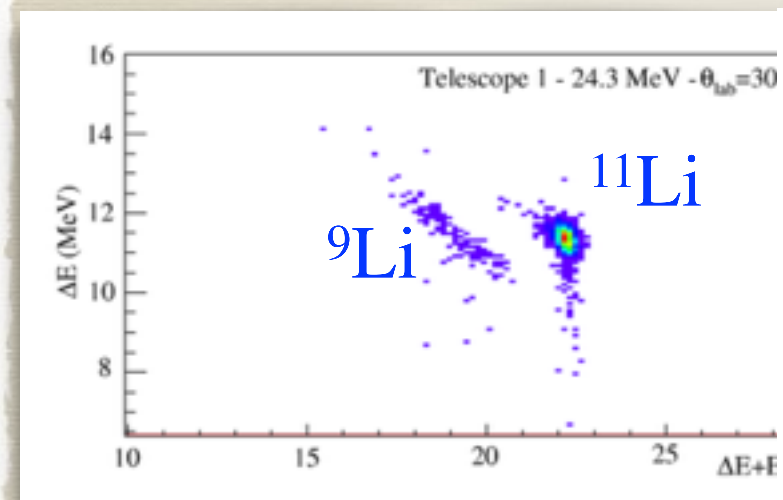
^{11}Li breakup @ Coulomb barrier

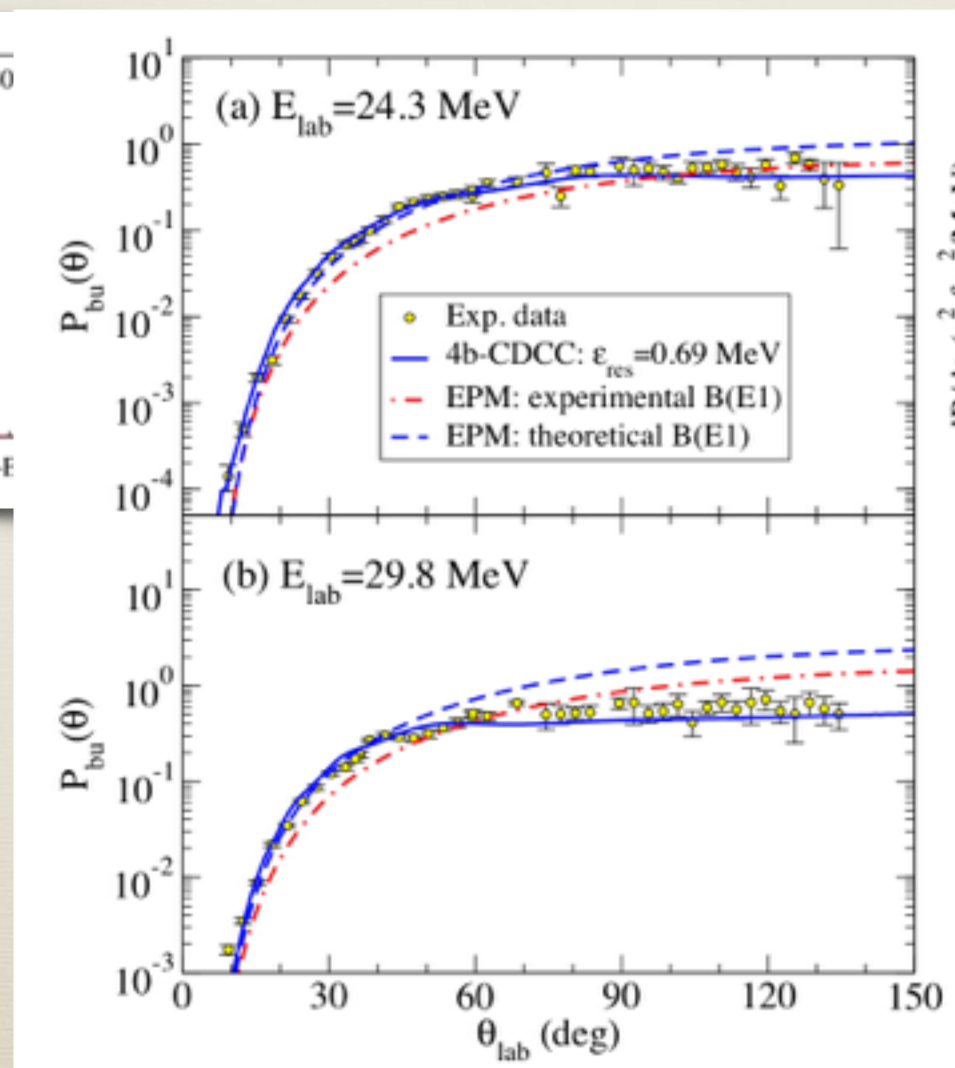
First measurement of breakup of ^{11}Li around the Coulomb barrier

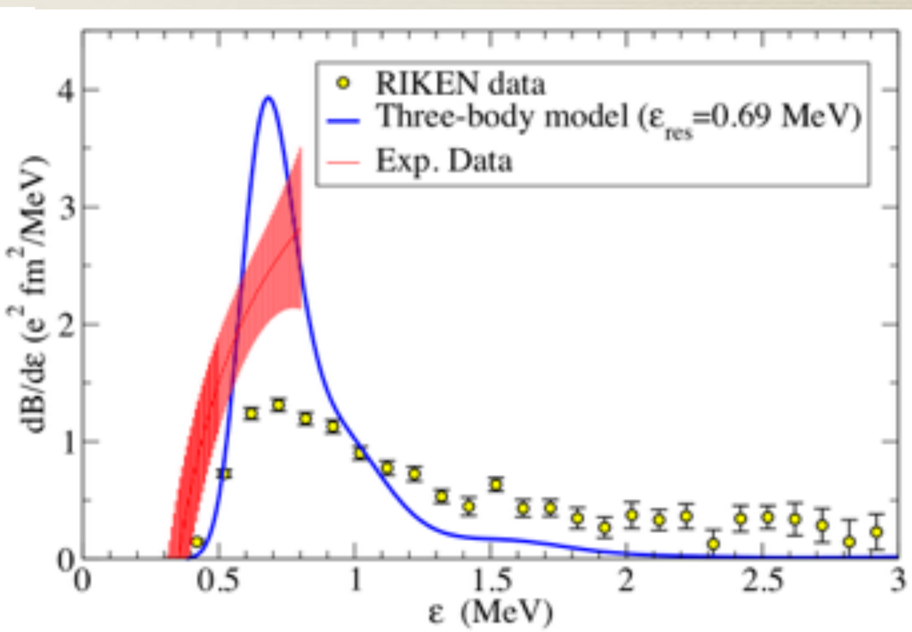
PRL **110**, 142701 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

^{11}Li Breakup on ^{208}Pb at Energies Around the Coulomb Barrier

J.P. Fernández García et al.







Substantial breakup probability found even below Coulomb barrier

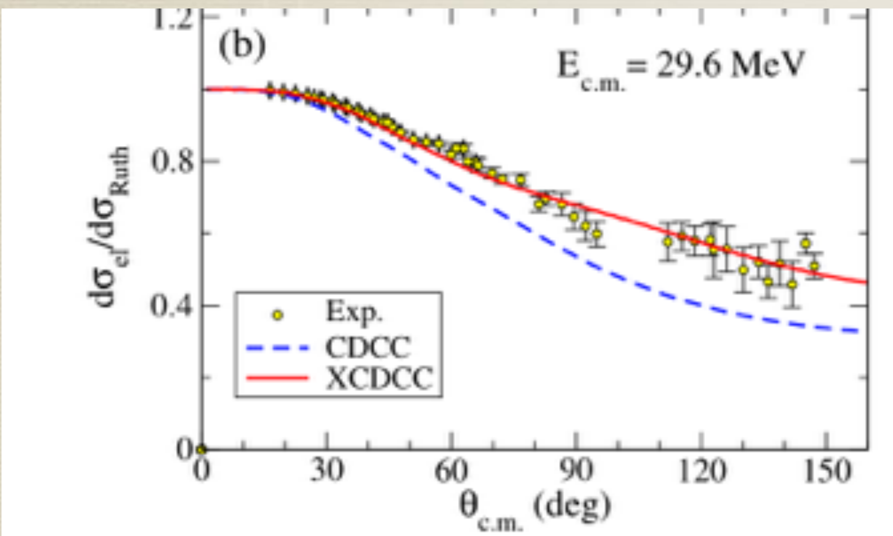
Breakup probability and B(E1) require ^{11}Li a dipole resonance ~ 0.7 MeV

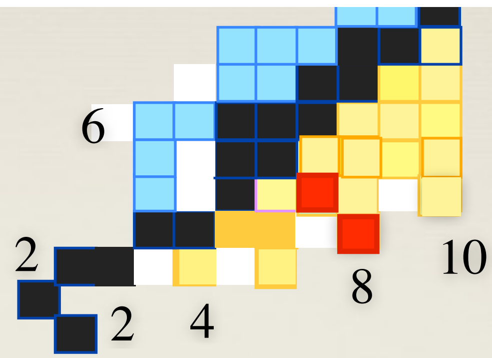
^{11}Be + Au near-barrier scattering @ TIGRESS

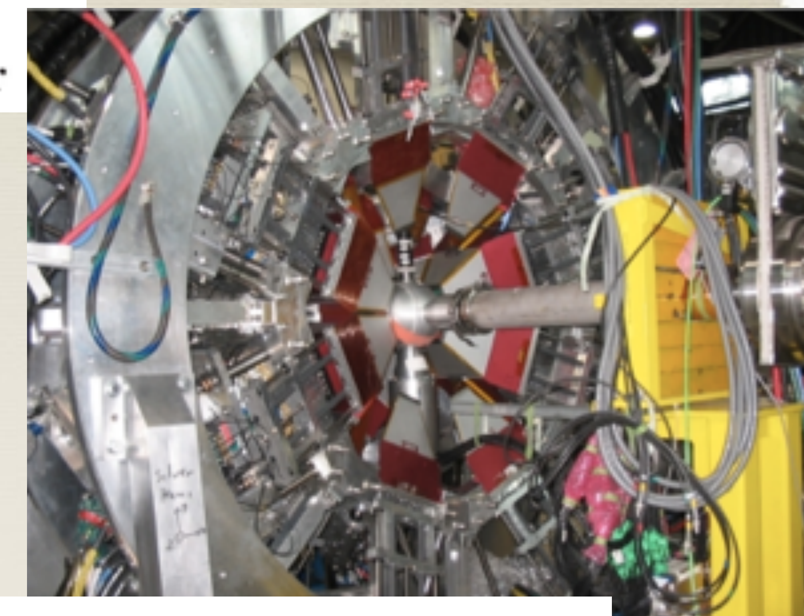
PRL **118**, 152502 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

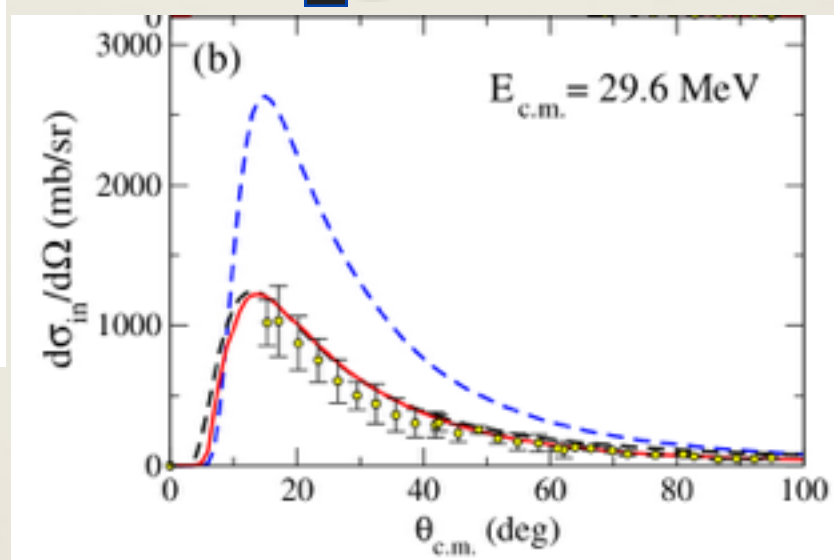
Scattering of the Halo Nucleus ^{11}Be on ^{197}Au at Energies around the Coulomb Barrier

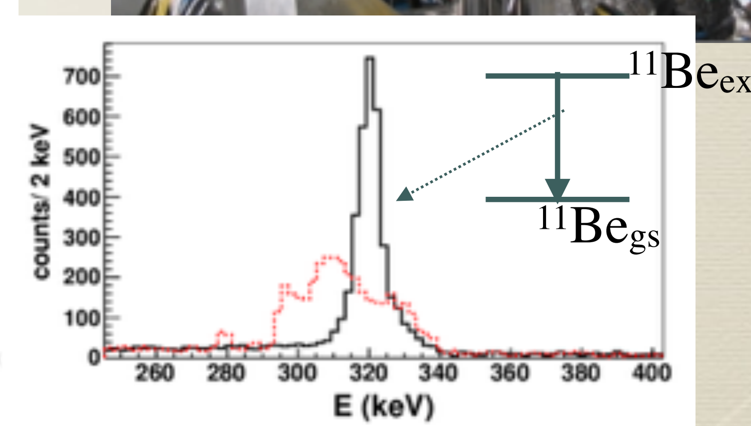
V. Pesudo et al.

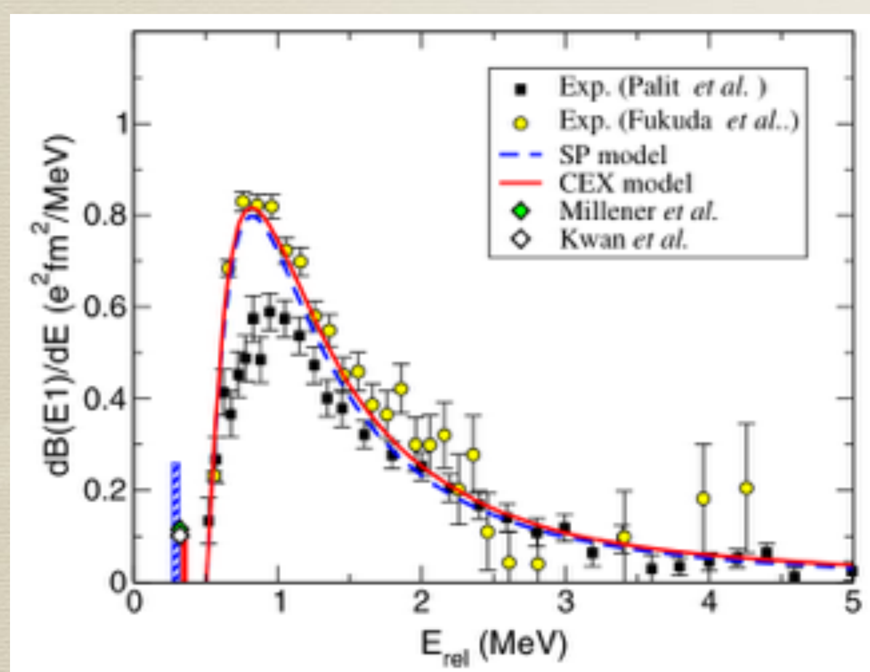






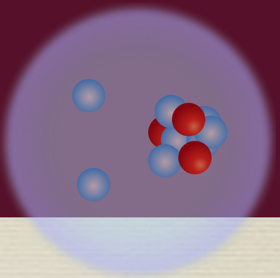






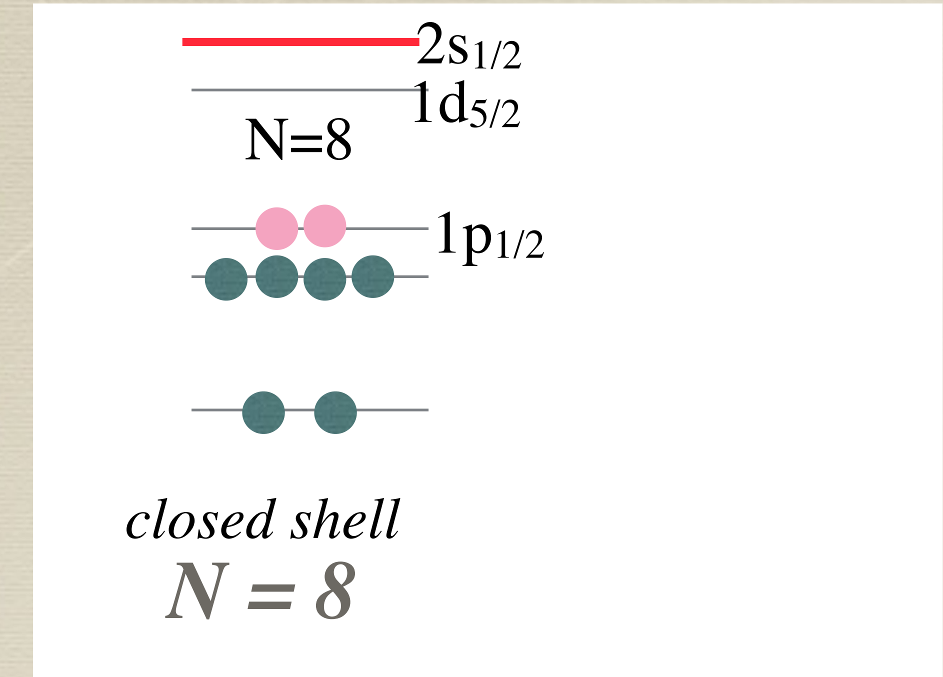
$^{11}Be_{gs} = 88\%(^{10}Be_{gs}) + 12\%(^{10}Be\text{-}2^+)$

^{11}Li halo breaks N = 8 shell

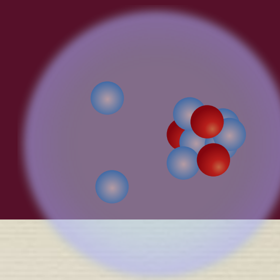


$^{11}_{3}Li_{8}$

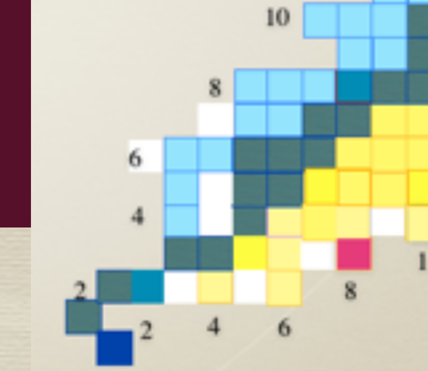
@ IRIS



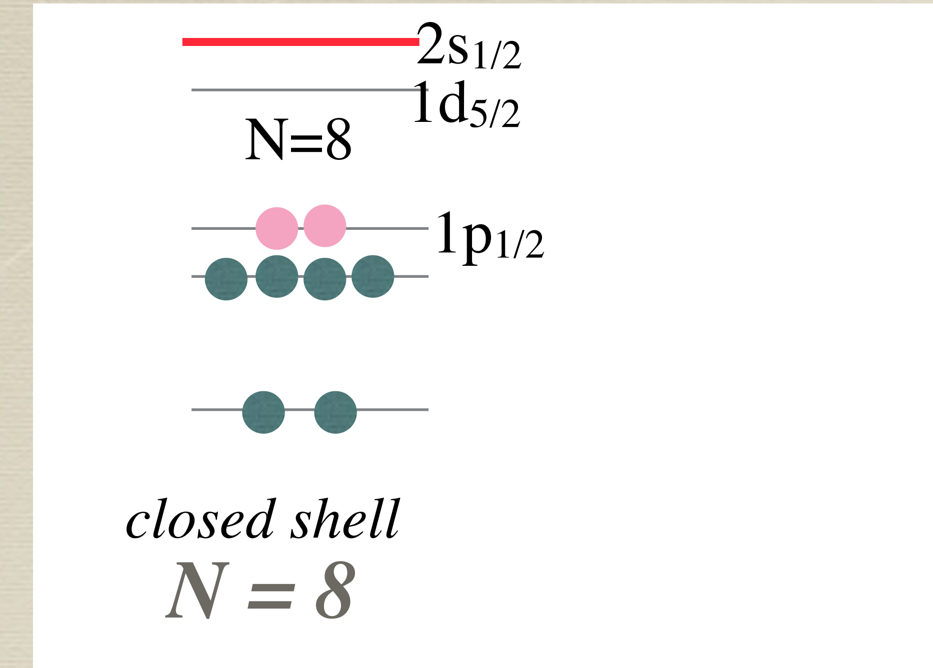
^{11}Li halo breaks N = 8 shell



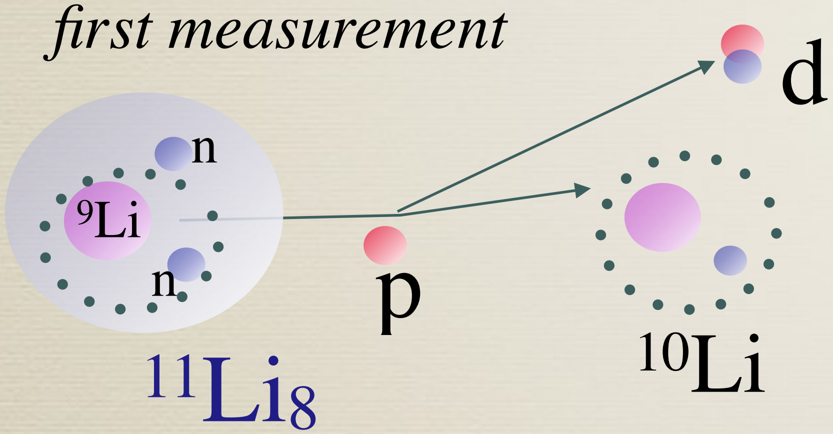
$^{11}{}_{3}Li_{8}$

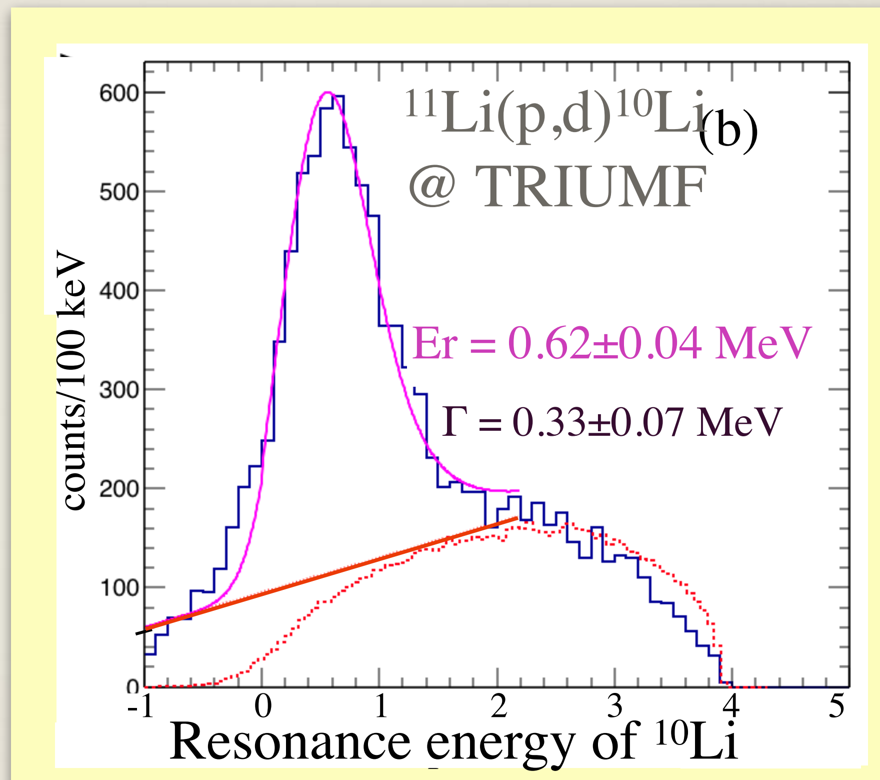


@ IRIS



first measurement

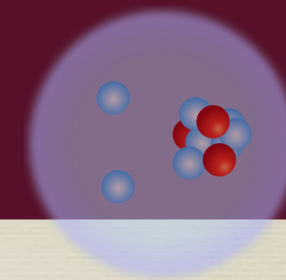


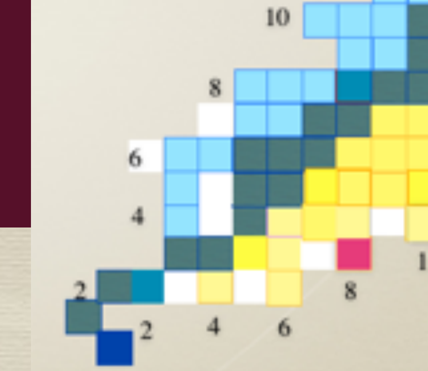


N = 8 closed shell ($p_{1/2}$) ~ 100%

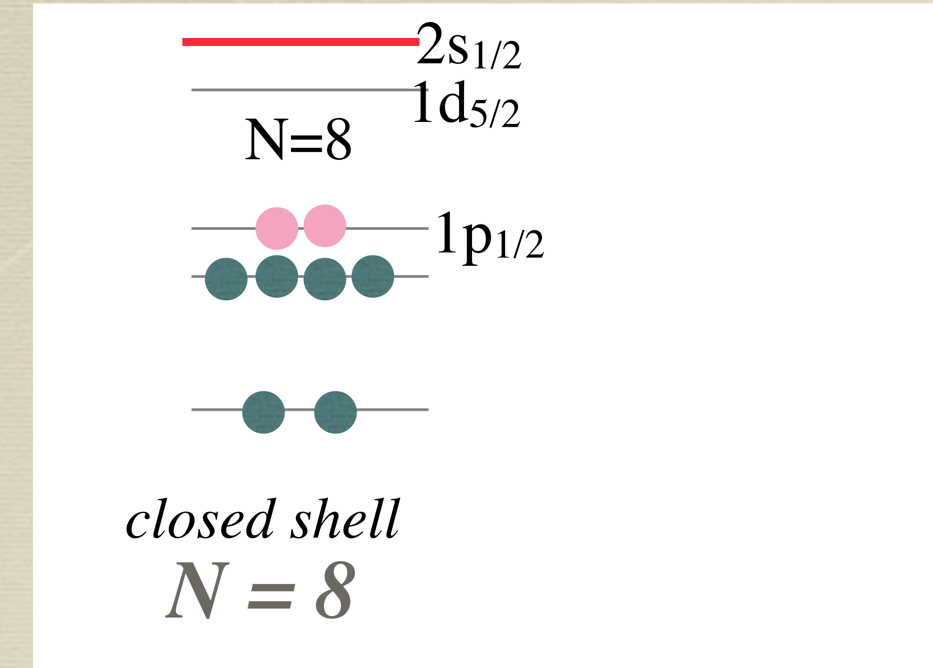
A. Sanetullaev, R.Kanungo et al., Phys. Lett. B 755 (2016) 481

^{11}Li halo breaks N = 8 shell

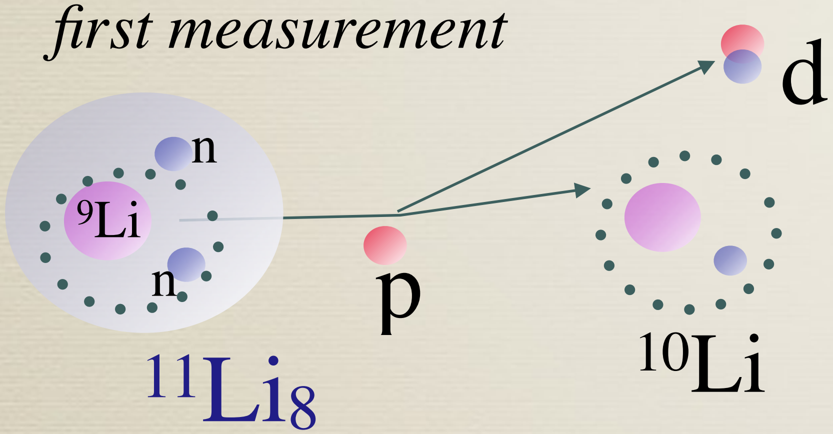


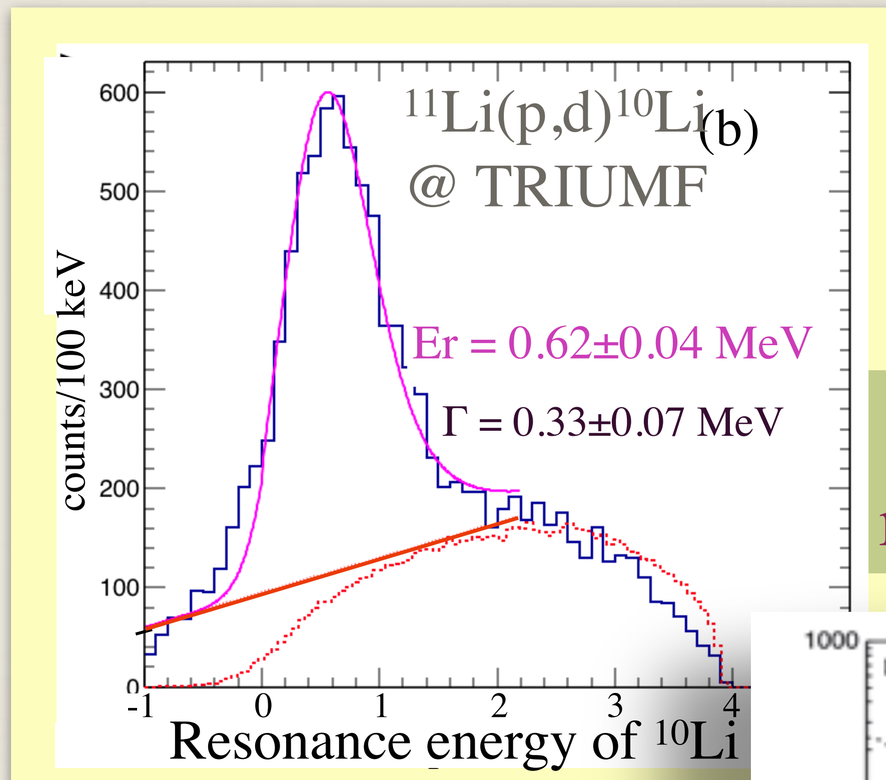


@ IRIS

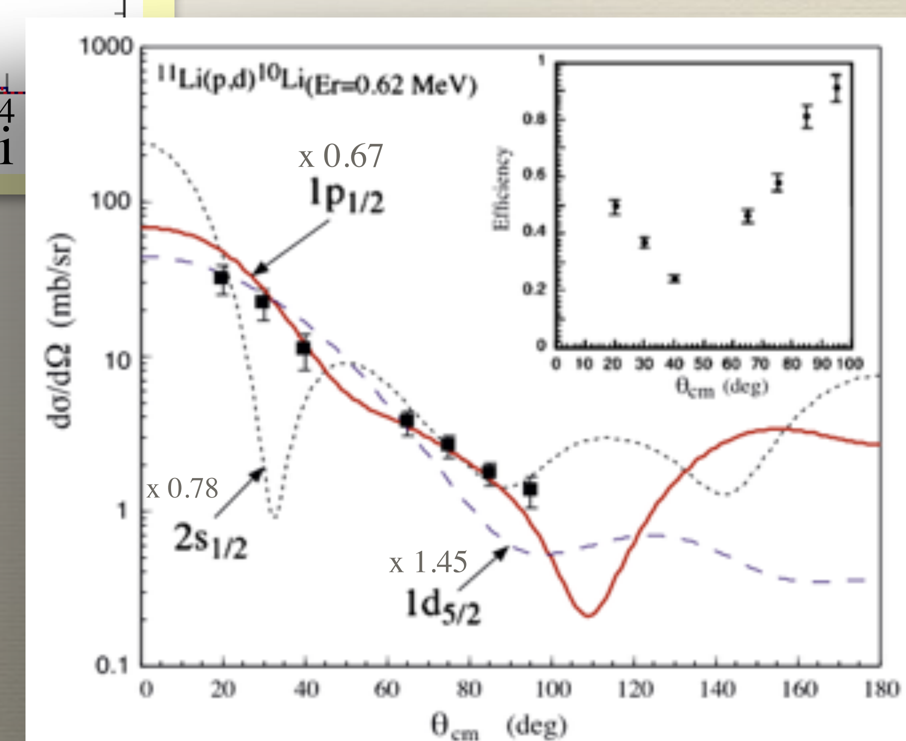


first measurement





L=1 resonance

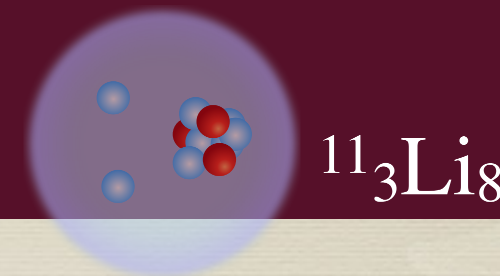


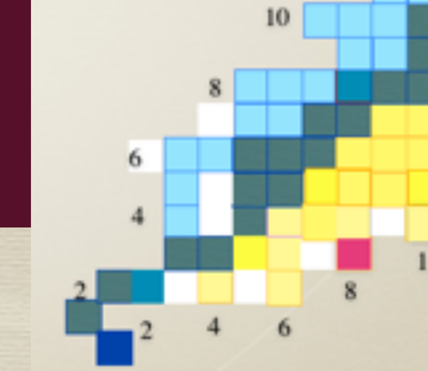
($p_{1/2}$) % = 33(12) %

N = 8 closed shell ($p_{1/2}$) ~ 100%

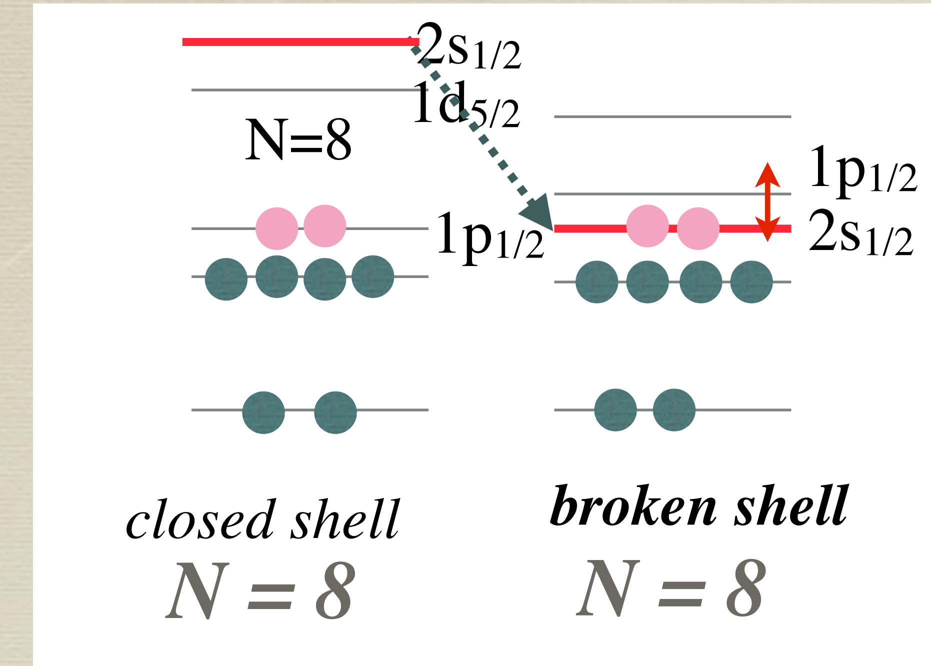
A. Sanetullaev, R.Kanungo et al., Phys. Lett. B 755 (2016) 481

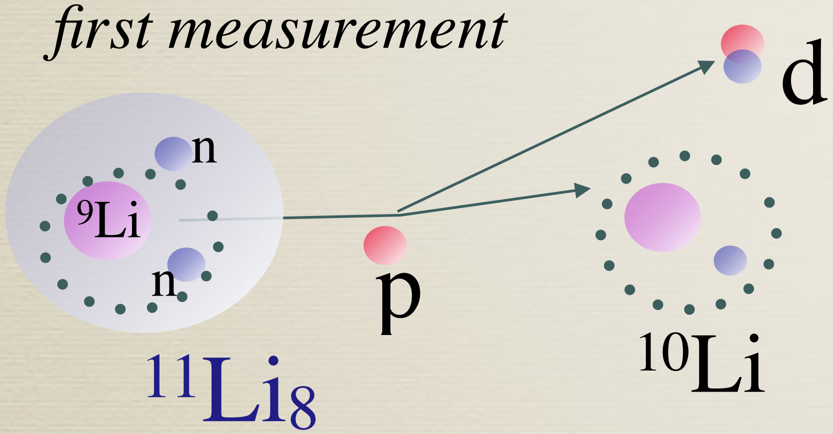
^{11}Li halo breaks N = 8 shell

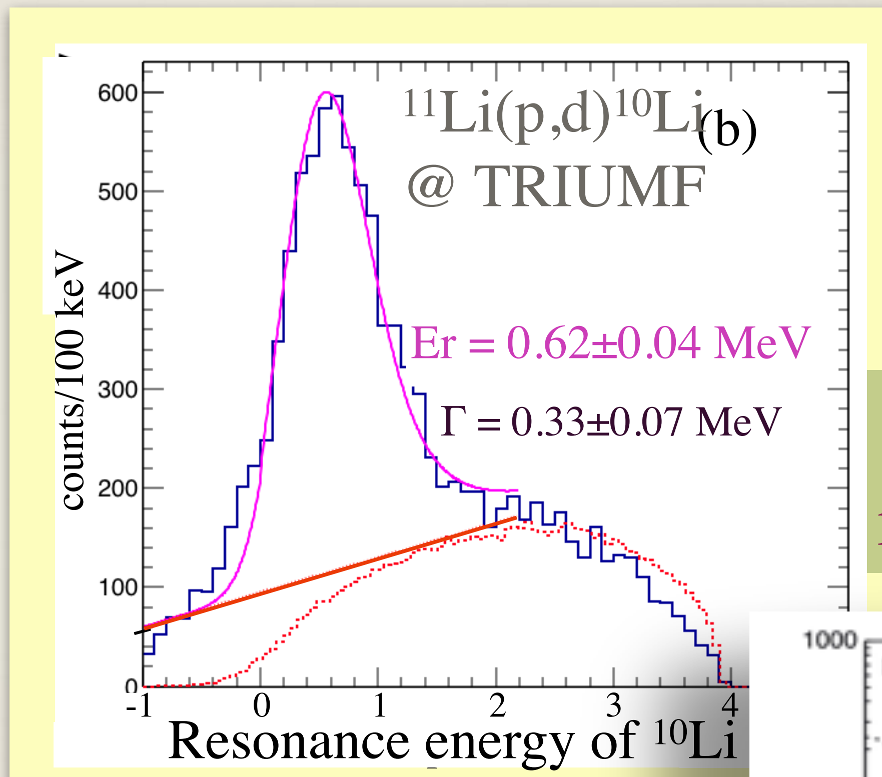




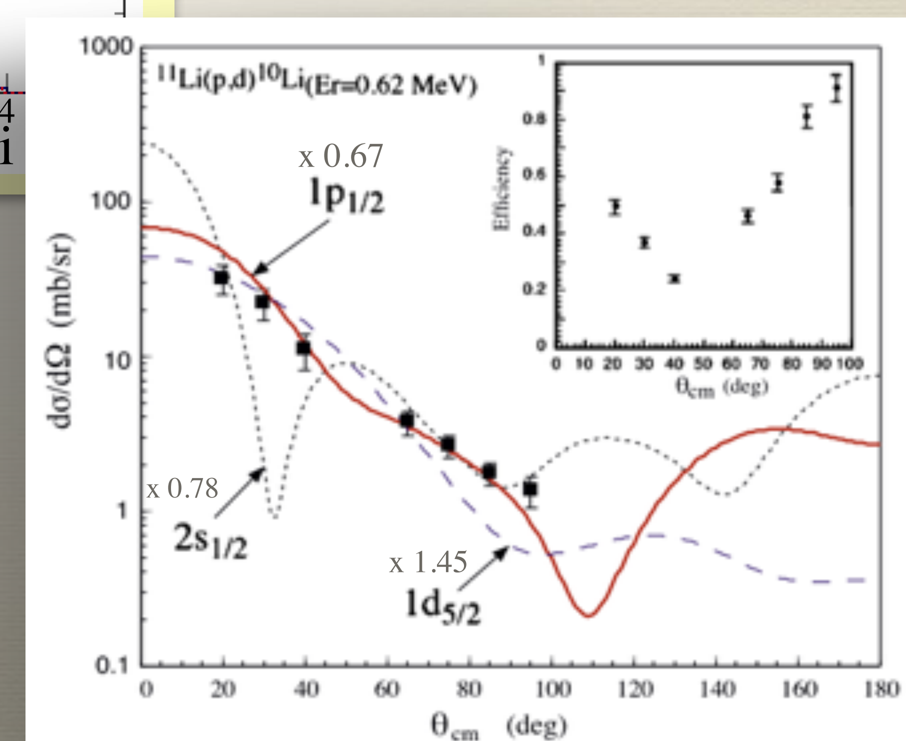
@ IRIS







L=1 resonance



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A. Sanetullaev, R.Kanungo et al., Phys. Lett. B 755 (2016) 481

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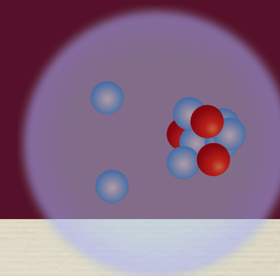
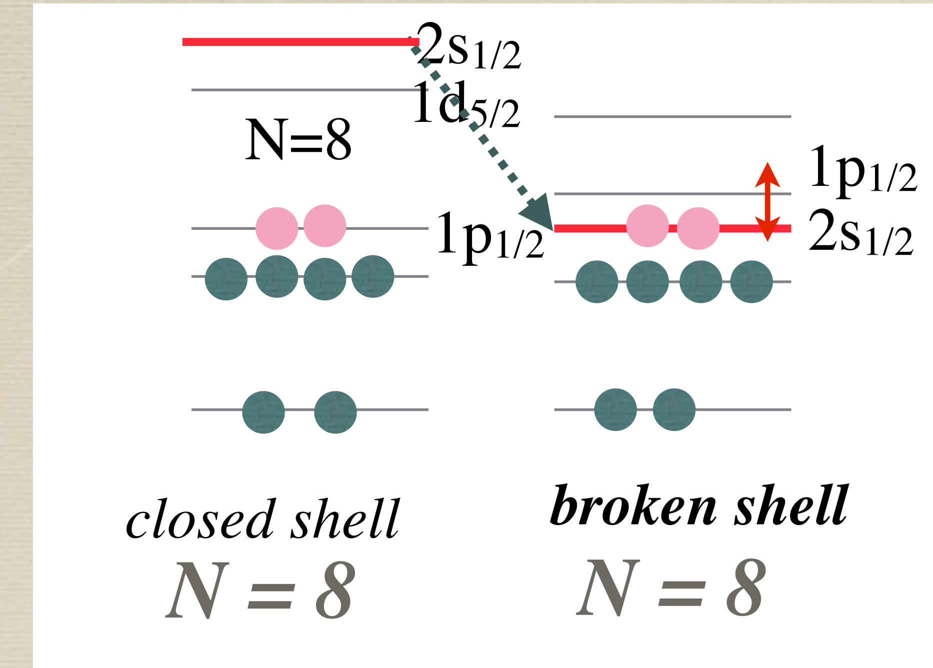


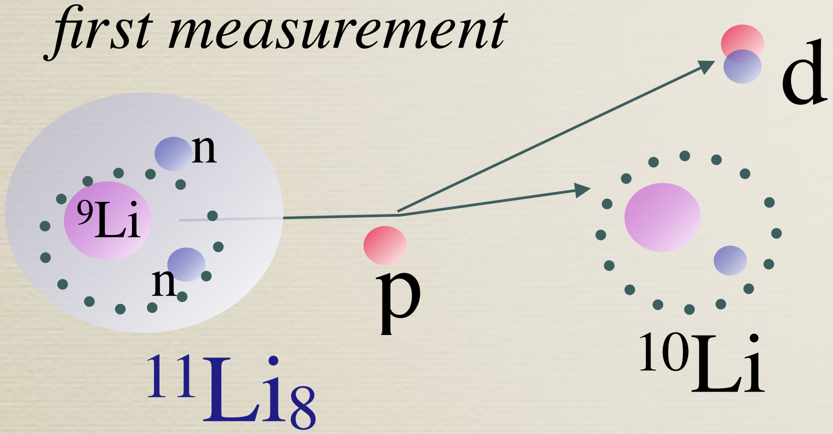


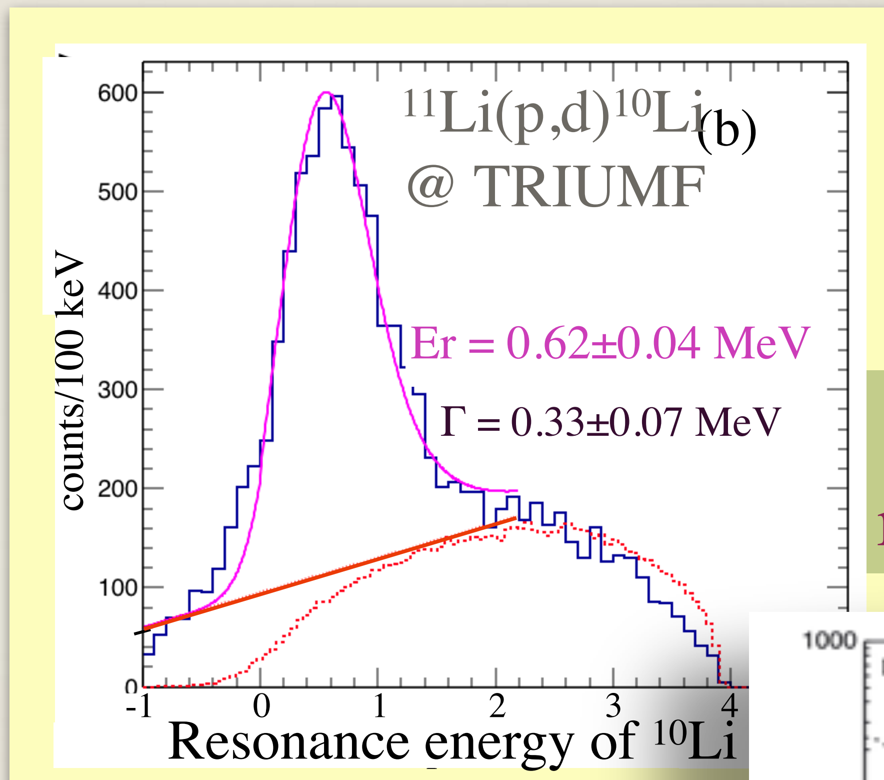
@ IRIS

s- p- mixing → correlation

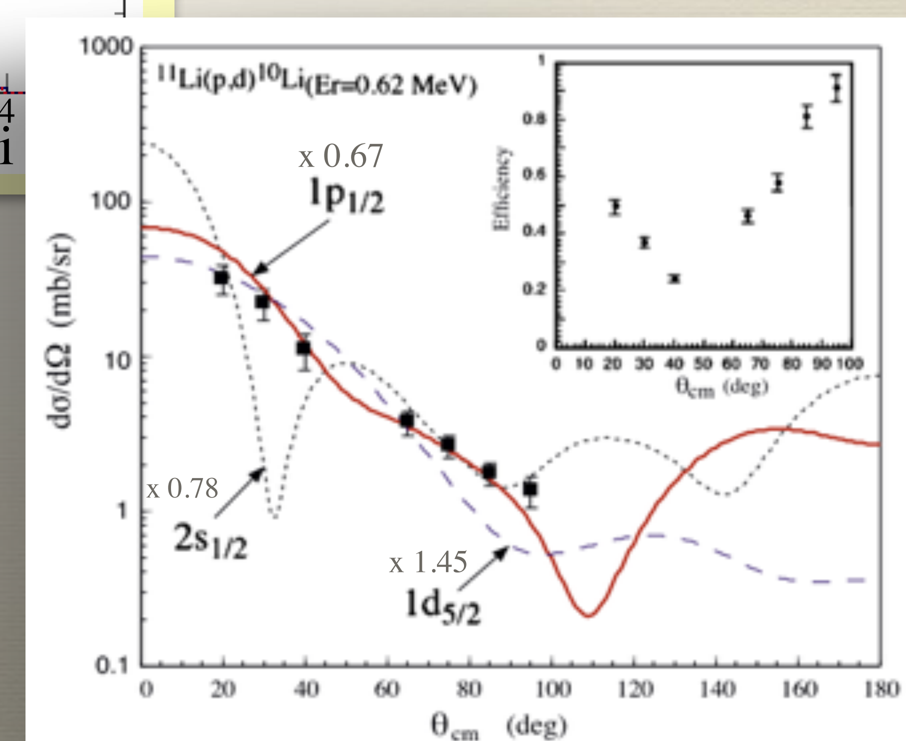
$2s_{1/2}$ → halo

first measurement





L=1
resonance



$(p_{1/2})$ % = 33(12) %

N = 8 closed shell $(p_{1/2})$ ~ 100%

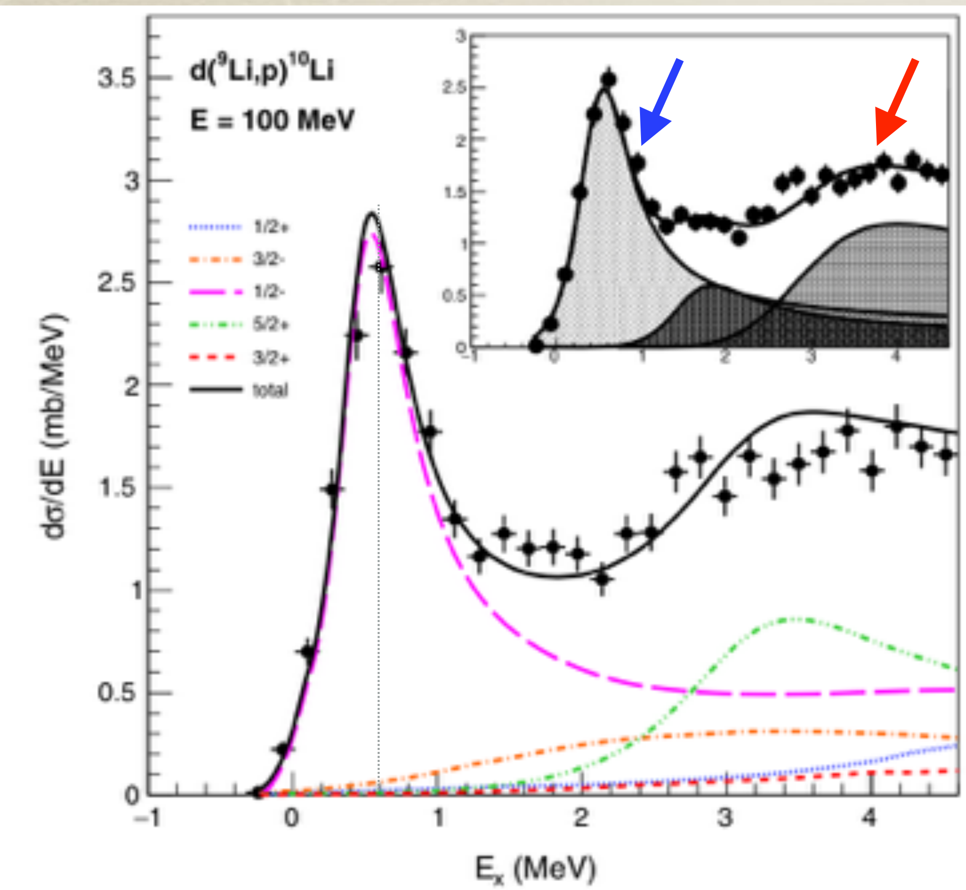
A. Sanetullaev, R.Kanungo et al., Phys. Lett. B 755 (2016) 481

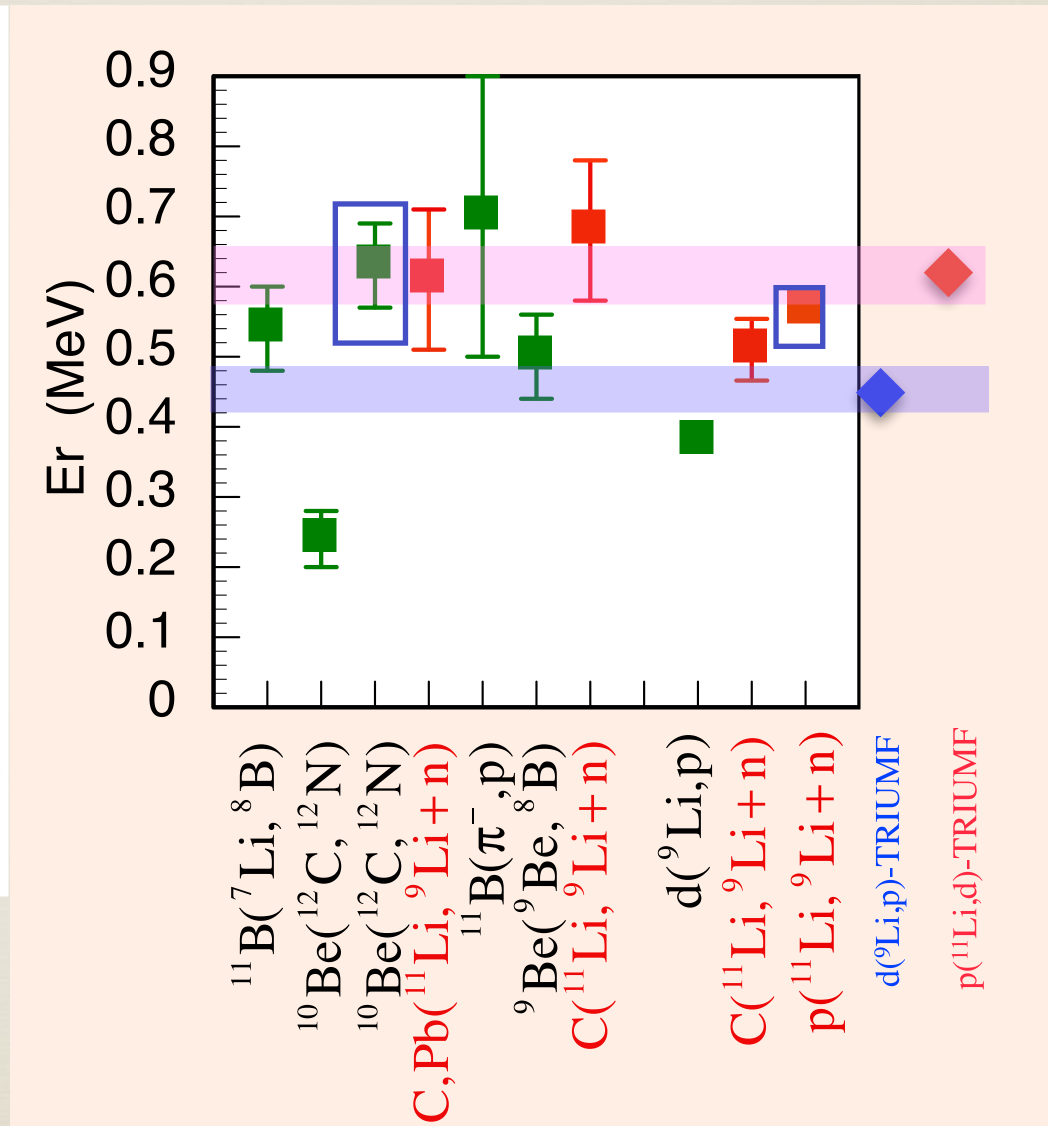
$^{9}Li(d,p)^{10}Li$ @ TUDA

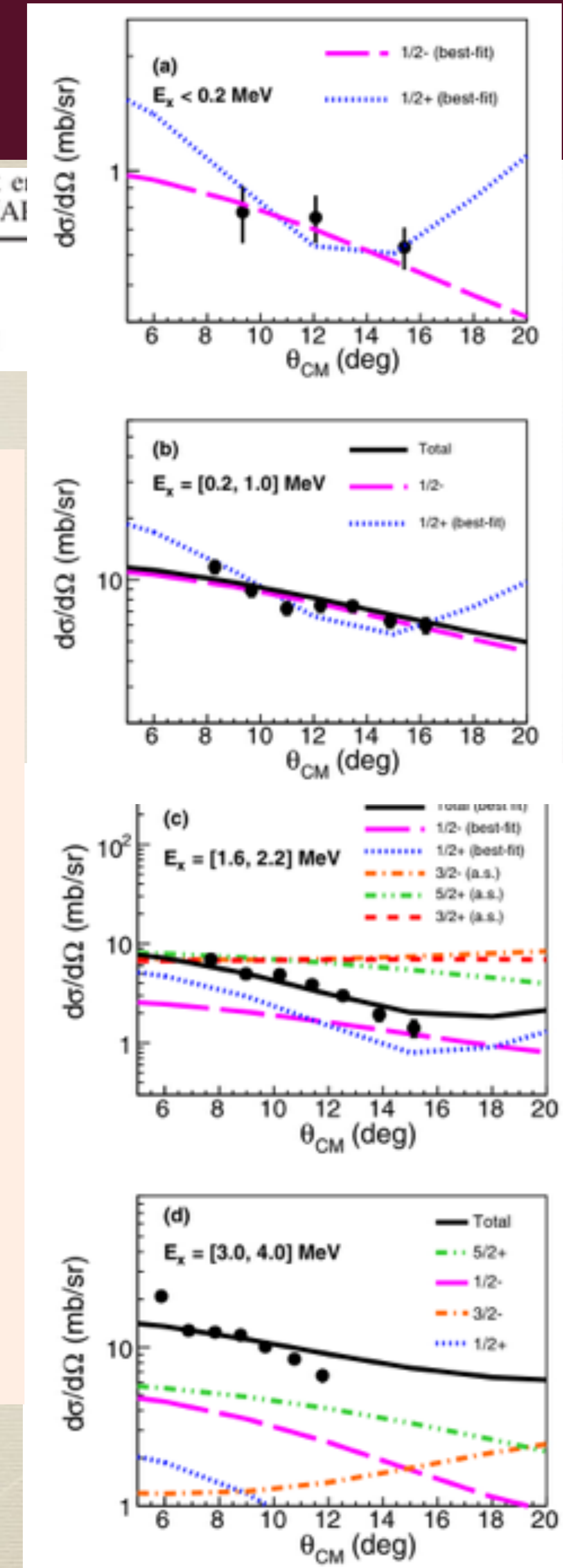
PRL **118,** 012701 (2017) PHYSICAL REVIEW LETTERS week e[…] 6 JANUA[…]

Investigation of the ^{10}Li shell inversion by neutron continuum transfer reaction

M. Cavallaro et al.







$E_r = 0.45 \pm 0.03$ MeV

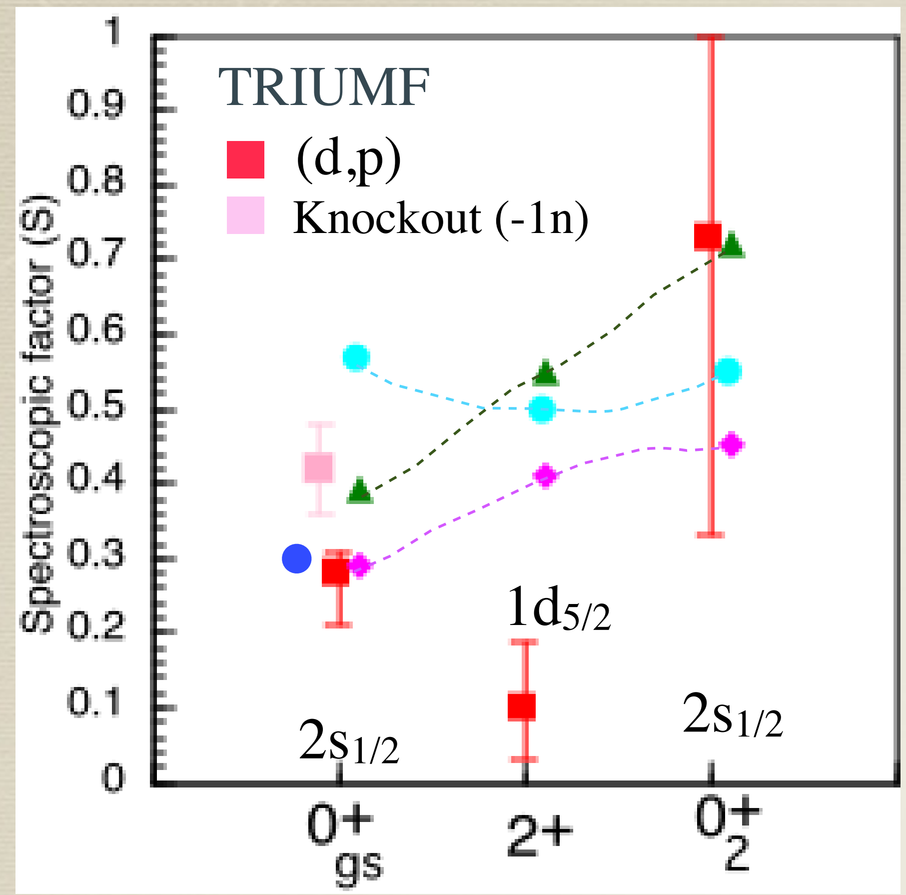
$\Gamma_r = 0.68 \pm 0.03$ MeV

Narrow low-energy resonance : p-wave

Broad high-energy resonance : d-wave

^{12}Be : Intruder *s*-orbital

^{11}Be(d,p)^{12}Be



R. Kanungo et al., Phys. Lett. B 682 (2010) 391.

◆ Δ_{psd} = -1.2, 42%N=0 + 58%N=2, $d_{5/2}$ lower 0.8 MeV

▲ Δ_{psd} = -1.85, 50%N=0 + 50%N=2

● Δ_{psd} = -1.85, 32%N=0 + 68%N=2

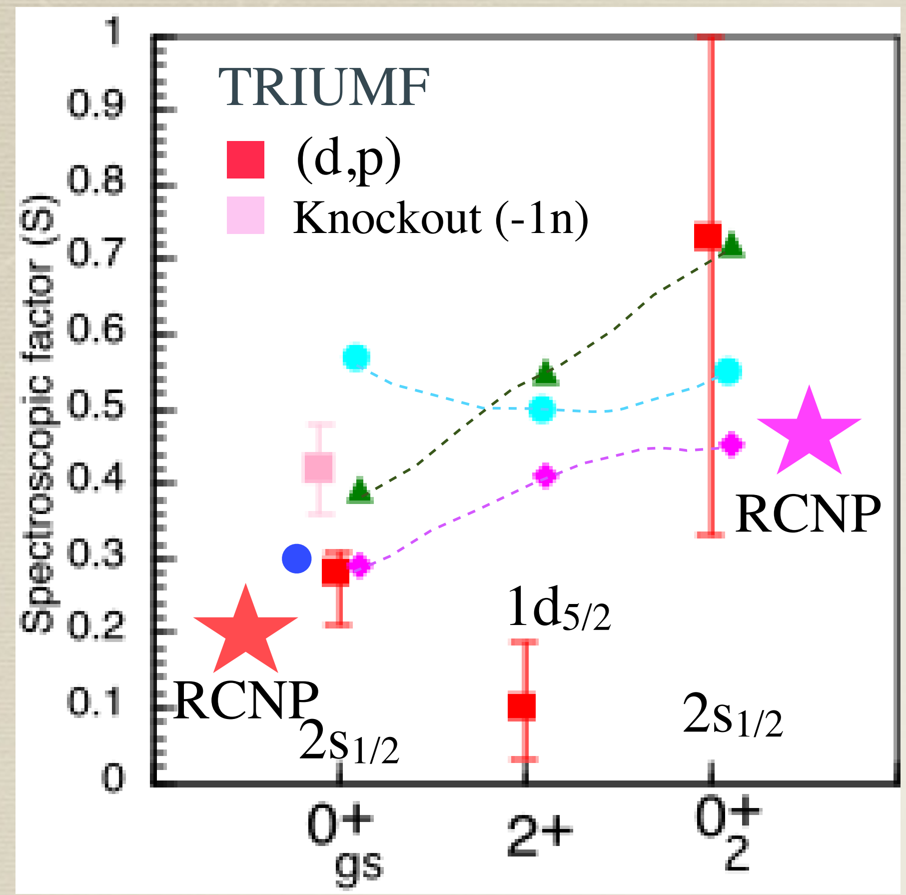
WBP

B.A. Brown

● G. Gori et al., PRC 69 ('04) 041302R (particle vibration +Av14)

^{12}Be : Intruder *s*-orbital

^{11}Be(d,p)^{12}Be



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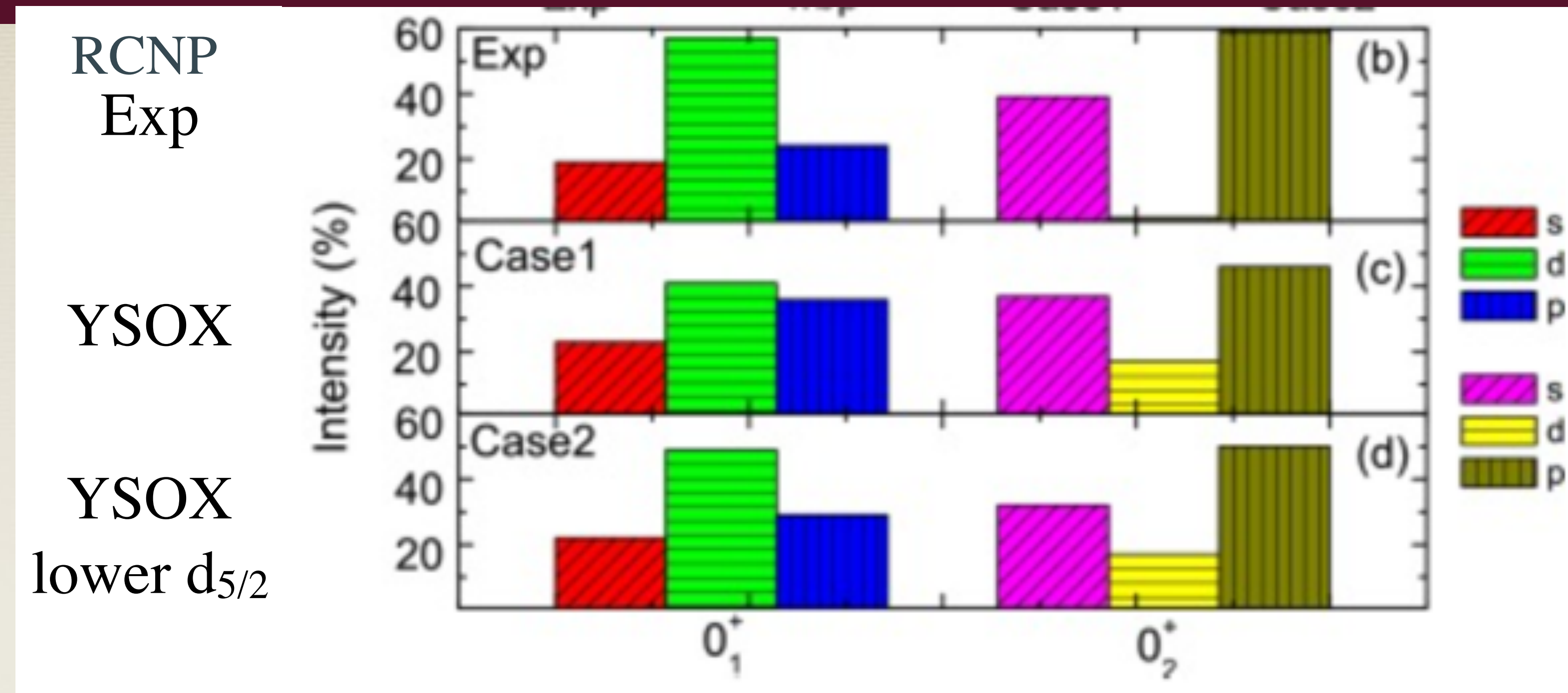

Higher $2s_{1/2}$ fraction in 0_2^+ state

J. Chen et al., Phys. Lett. B 781 (2018) 412

- ◆ Δ_{psd} = -1.2, 42%N=0 + 58%N=2, $d_{5/2}$ lower 0.8 MeV
- ▲ Δ_{psd} = -1.85, 50%N=0 + 50%N=2
- ● Δ_{psd} = -1.85, 32%N=0 + 68%N=2

WBP

B.A. Brown

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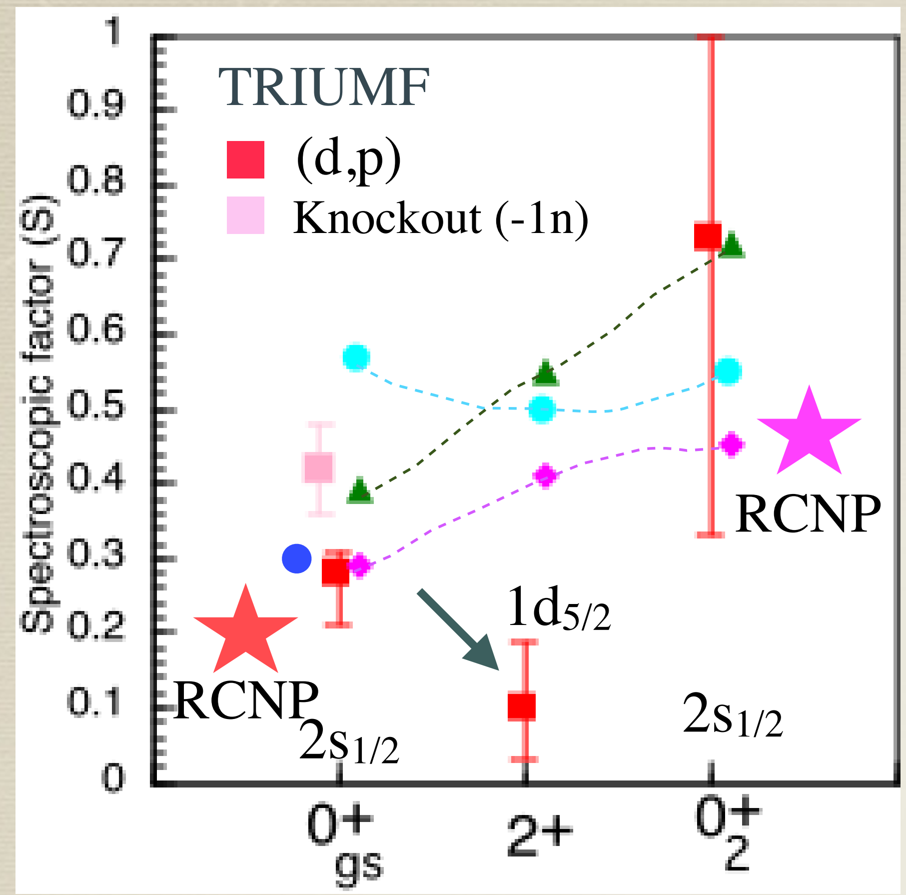
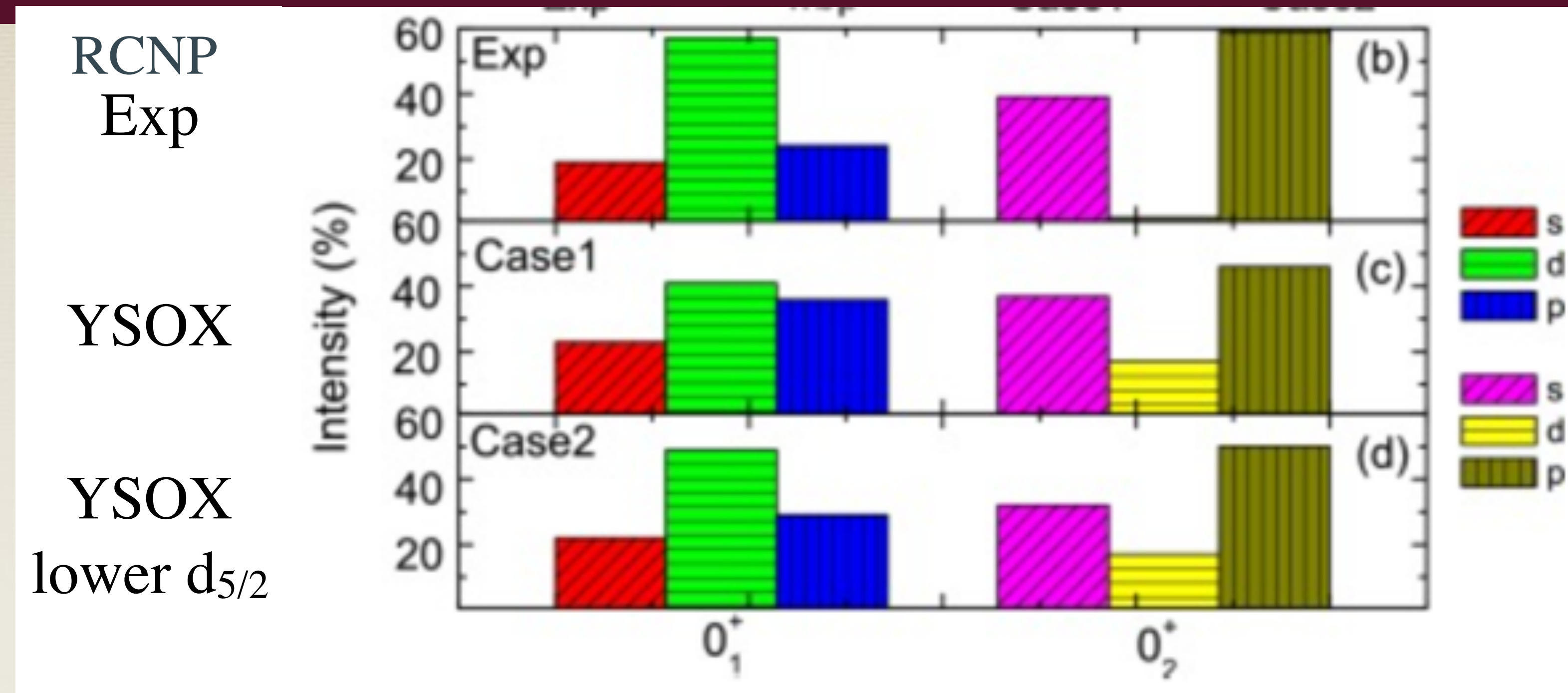


R. Kanungo et al., Phys. Lett. B 682 (2010) 391.

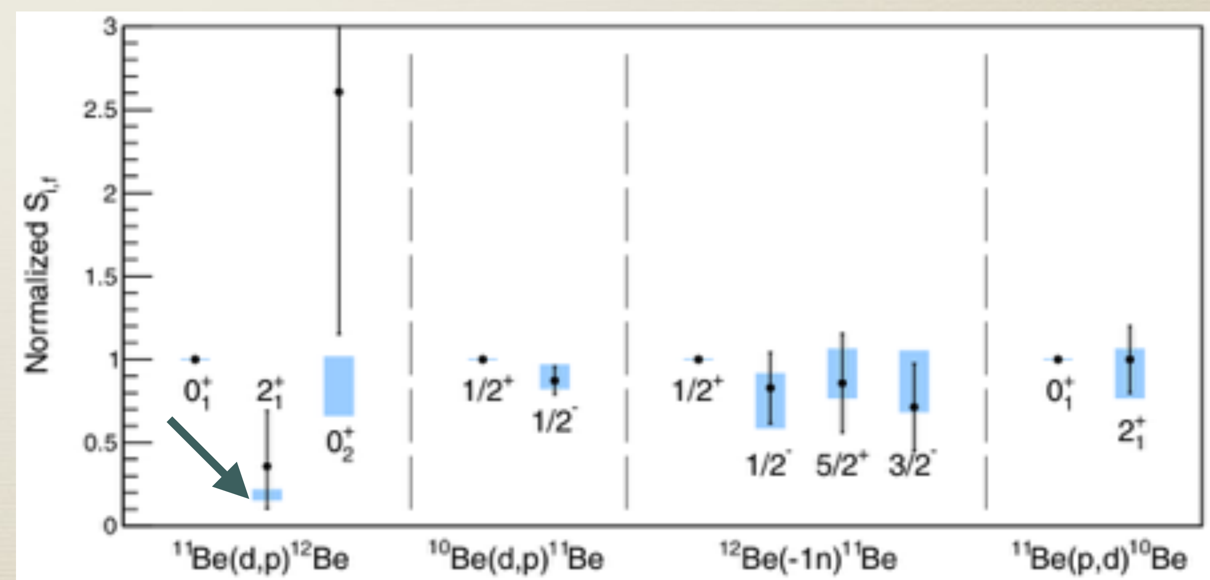


Higher $2s_{1/2}$ fraction in 0_2^+ state

J. Chen et al., Phys. Lett. B 781 (2018) 412

◆ (pink)	Δ_{psd} = -1.2, 42%N=0 + 58%N=2, $d_{5/2}$ lower 0.8 MeV	WBP
▲ (green)	Δ_{psd} = -1.85, 50%N=0 + 50%N=2	
● (cyan)	Δ_{psd} = -1.85, 32%N=0 + 68%N=2	
		B.A. Brown
● (blue)	G. Gori et al., PRC 69 ('04) 041302R (particle vibration +Av14)	

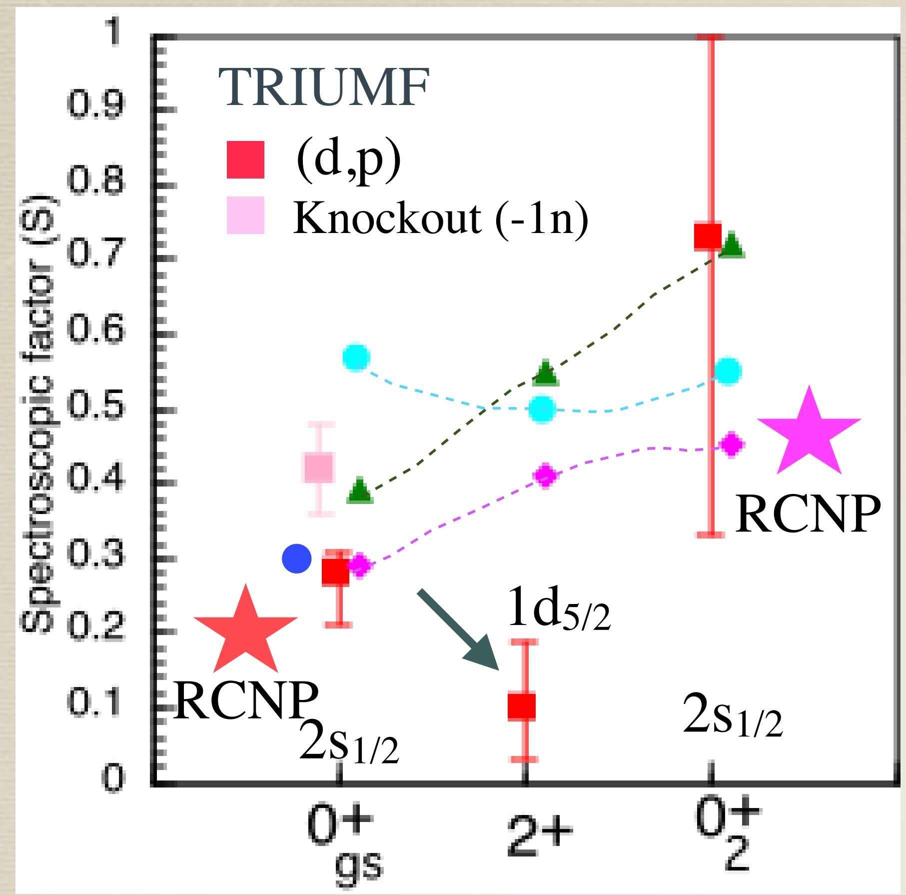
Nilsson strong coupling limit

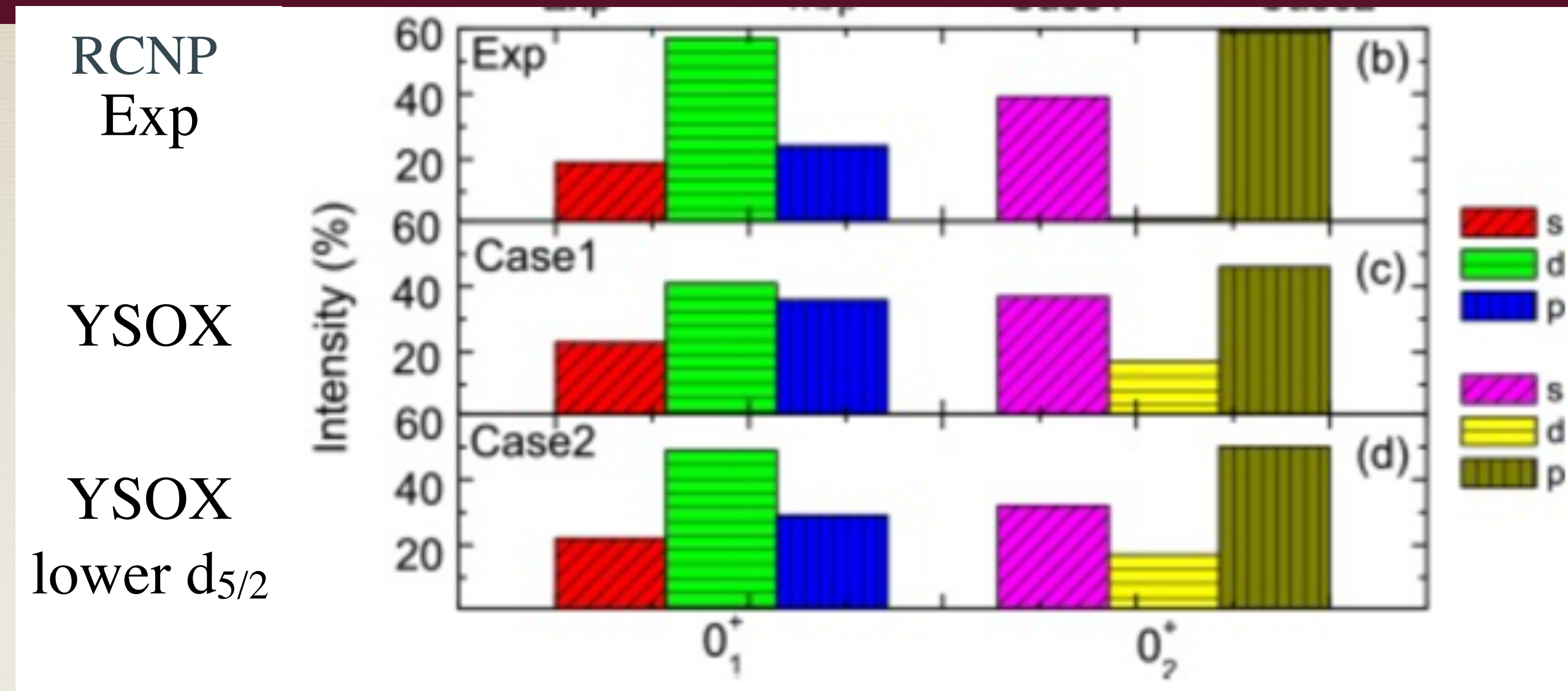


A.O. Machchiavelli, H.L. Crawford et al., Phys. Rev. C 97 (2018) 011302R

^{12}Be : Intruder *s*-orbital

^{11}Be(d,p)^{12}Be





Higher $2s_{1/2}$ fraction in 0_2^+ state

J. Chen et al., Phys. Lett. B 781 (2018) 412

Nilsson strong coupling limit

^{12}Be$_{gs}$: small $2s_{1/2}$, large $1d_{5/2}$ fraction

$d_{5/2}$ lower 0.8 MeV

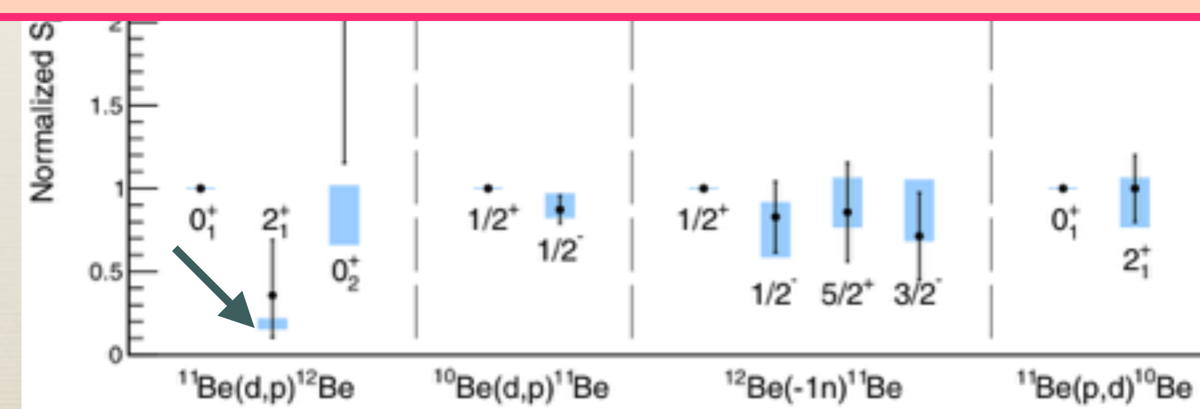
▲ Δ_{psd} = -1.85, 50%N=0 + 50%N=2

● Δ_{psd} = -1.85, 32%N=0 + 68%N=2

WBP

B.A. Brown

● G. Gori et al., PRC 69 ('04) 041302R (particle vibration +Av14)



A.O. Machchiavelli, H.L. Crawford et al., Phys. Rev. C 97 (2018) 011302R

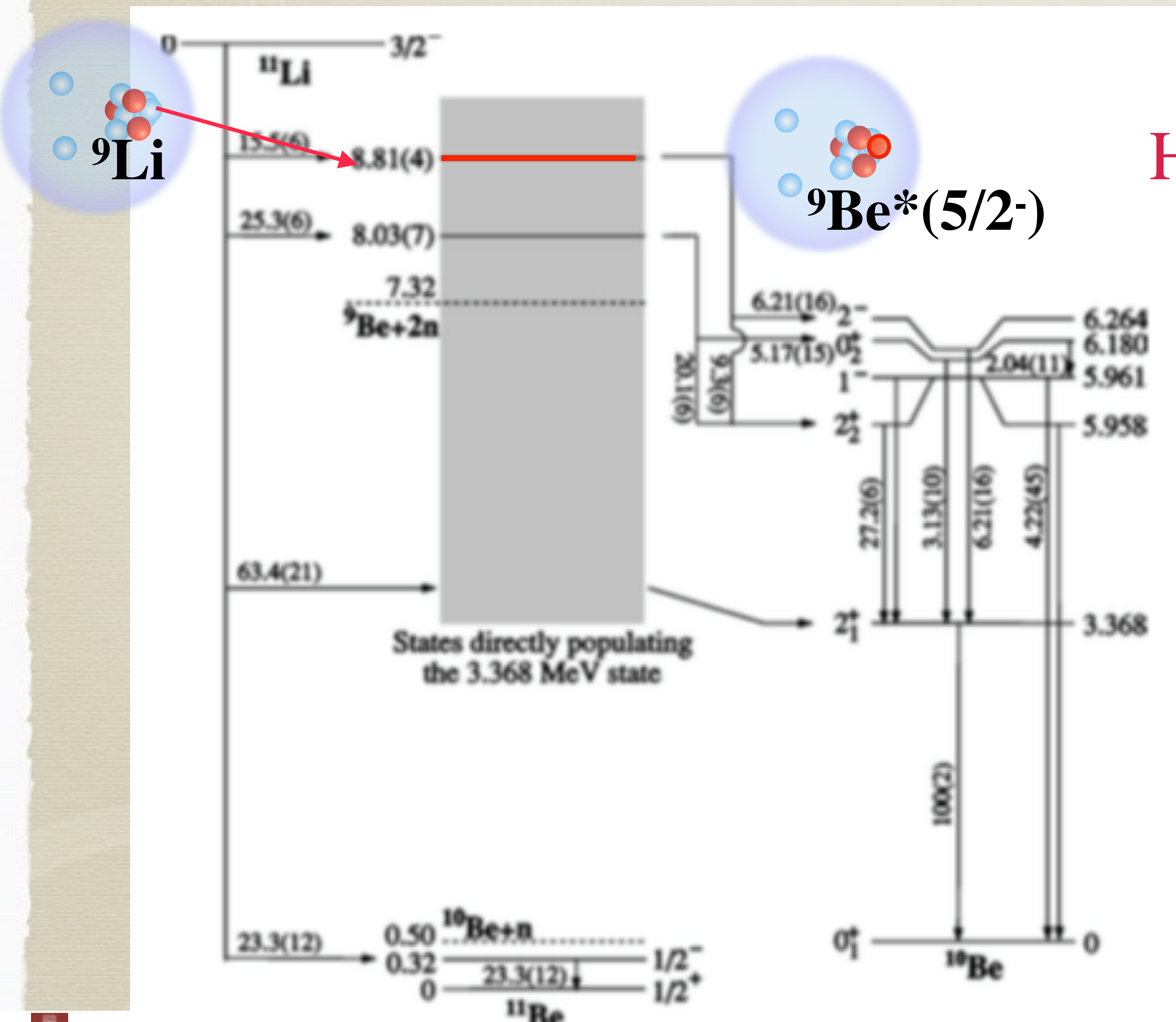
^{11}Li Beta decay : preserves halo as excited ^{11}Be

RAPID COMMUNICATIONS

PHYSICAL REVIEW C 70, 031302(R) (2004)

Halo neutrons and the β decay of ^{11}Li

F. Sarazin et al.



Halo in excited state of ^{11}Be

$$B(E1;2^- \rightarrow 2^+)_{Ex} = 7.7\times10^{-4}W.u.$$

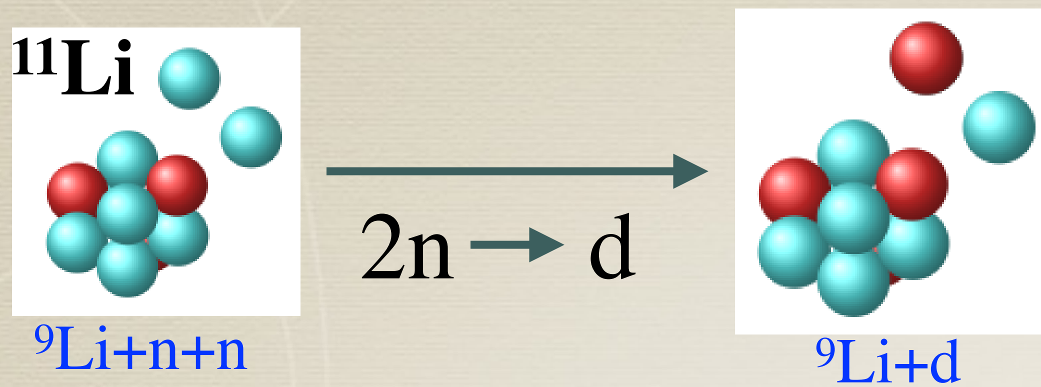
$$B(E1;2^- \rightarrow 2^+)_{Theo} = 0.02W.u.$$

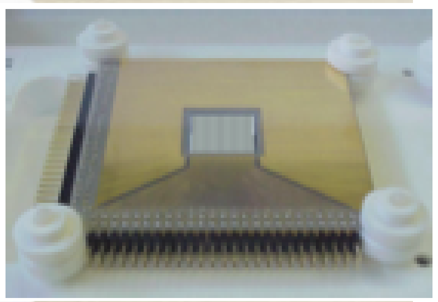
^{11}Li Halo decay

PRL 101, 212501 (2008) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2008

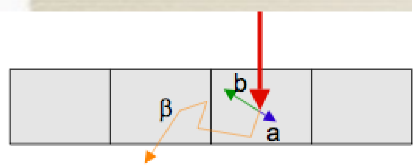
β-Delayed Deuteron Emission from ^{11}Li: Decay of the Halo

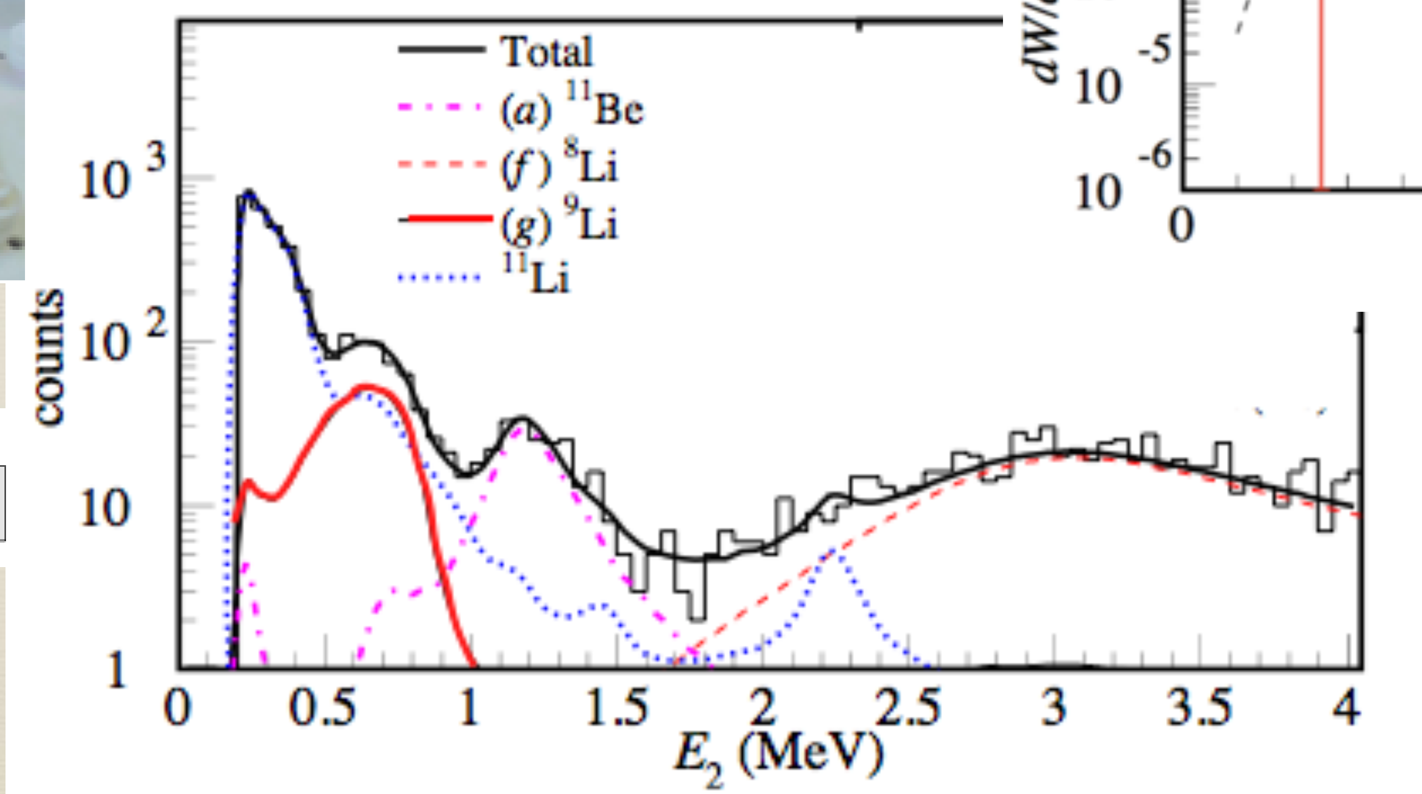
R. Raabe et al.

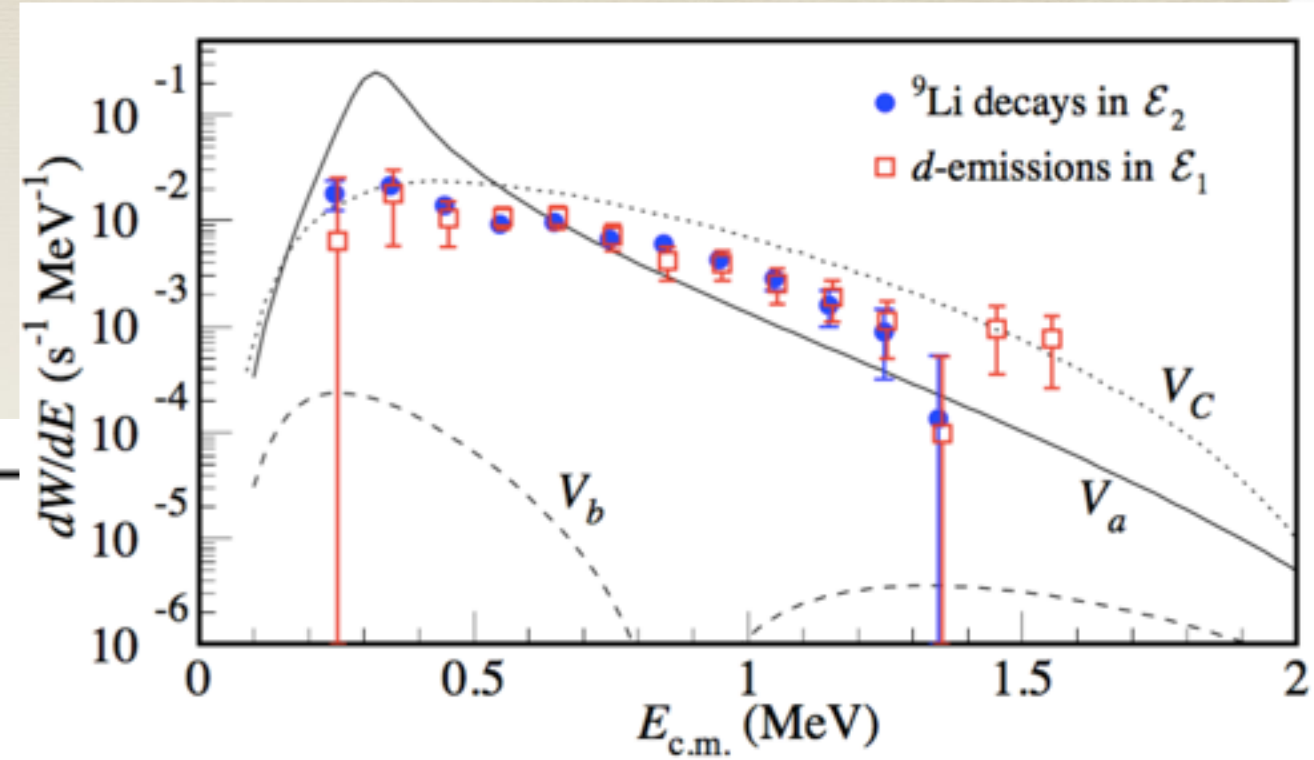




16mm x16mm







^{9}Li + d potentials

- V_a: resonance in ^{9}Li + d 0.33 MeV above threshold
- V_b: bound state in ^{9}Li + d 0.18 MeV below threshold
- V_C: only (Coulomb-distorted) plane wave

- **Large branching ratio $B_d = 1.3 \times 10^{-4}$** (^{6}He : $B_d \sim 10^{-6}$)
- **Decay proceeds directly to continuum.**

This will be useful to constrain the wavefunction of ^{11}Li

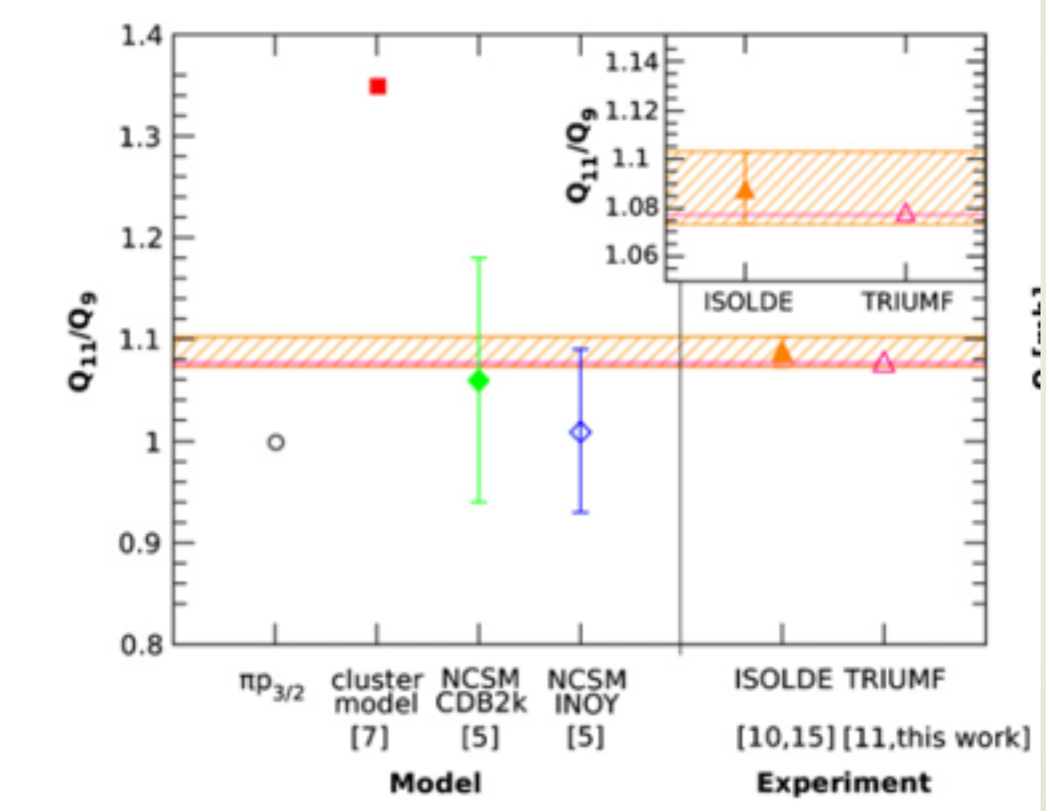
^{11}Li : Quadrupole moment

Journal of Physics G: Nuclear and Particle Physics

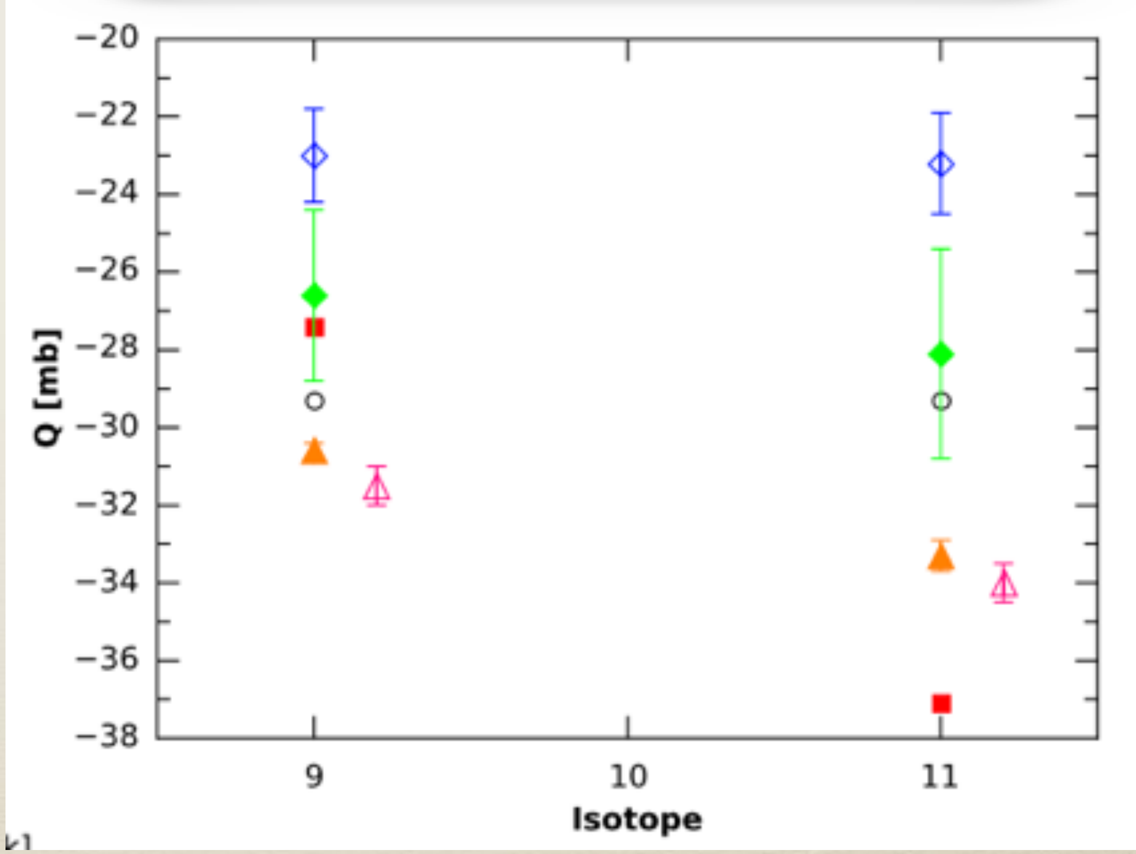
High precision measurement of the ^{11}Li and ^{9}Li quadrupole moment ratio using zero-field β-NQR

A. Voss et al. (2013)

Most precise measurement of quadrupole moment ratio of ^{9}Li/^{11}Li



$$\frac{Q\left(^{11}\mathrm{Li}\right)}{Q\left(^{9}\mathrm{Li}\right)} = 1.0775(12)[0]$$

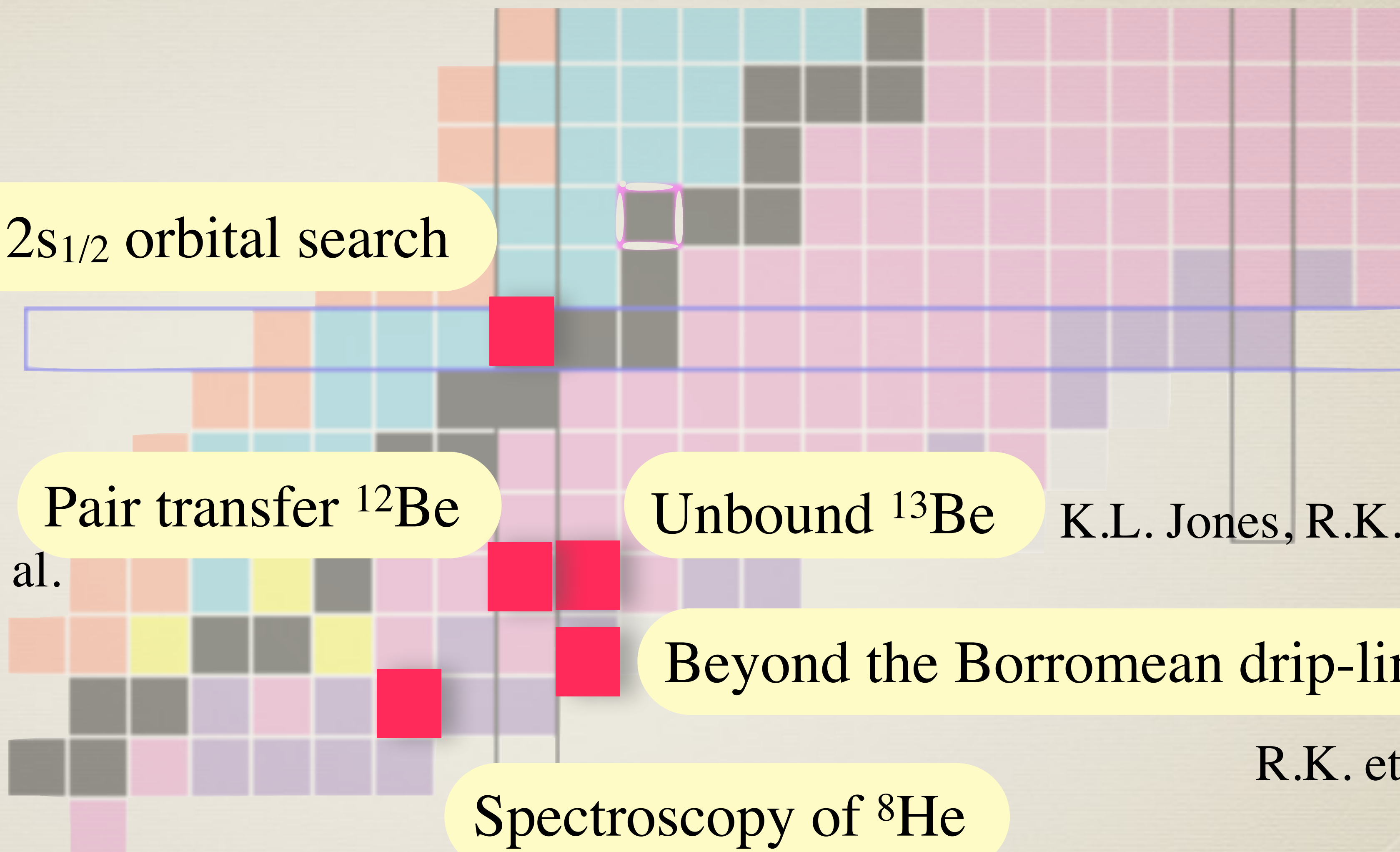


Summary

20 years of ISAC-beams - **^{11}Li TRIUMF's signature beam** - made pioneering measurements in unveiling the neutron halo

TITAN	: ^{11}Li shortest half-life measured most precisely
Isotope Shift	: First Charge radius of halo ^{11}Li -> Halo correlation
Active Target	: First pair transfer halo ^{11}Li -> Halo correlation, phonon mediated pairing
IRIS	: Established soft dipole resonance in ^{11}Li, found resonance in ^{10}Li
TUDA	: Found p- and d- wave resonance in ^{10}Li
Silicon setup	: Below barrier Coulomb scattering and breakup - Halo dipole coupling effect seen
TIGRESS	: Halo configuration in ^{11}Be and ^{12}Be
8 - pi	: Observed halo preserved in excited daughter state in ^{11}Li β-decay
Silicon implantation	: First measurement of halo neutron decay in ^{11}Li
β-NQR	: Most precise measurement of quadrupole moment of ^{9,11}Li

Look Ahead



Proton Halo in ^{17}Ne - 2s$_{1/2}$ orbital search
I. Martel et al.
Pair transfer ^{12}Be
R.K. et al.
Unbound ^{13}Be
K.L. Jones, R.K. et al.
Beyond the Borromean drip-line : ^{12}Li
R.K. et al.
Spectroscopy of ^{8}He
M. Holl et al.

Halo explorers @ TRIUMF from around the world

Happy 20th Anniversary !!

Thank you to TRIUMF - ISAC for enabling a glorius period of pioneering experiments with Halo beams

Looking forward to Many Many Happy Returns of decades of new discoveries with ARIEL-beams

Remembering our treasured colleagues who we lost along the journey

John D'Auria

Pat Walden

Randy Churchman

Grant Sheffer