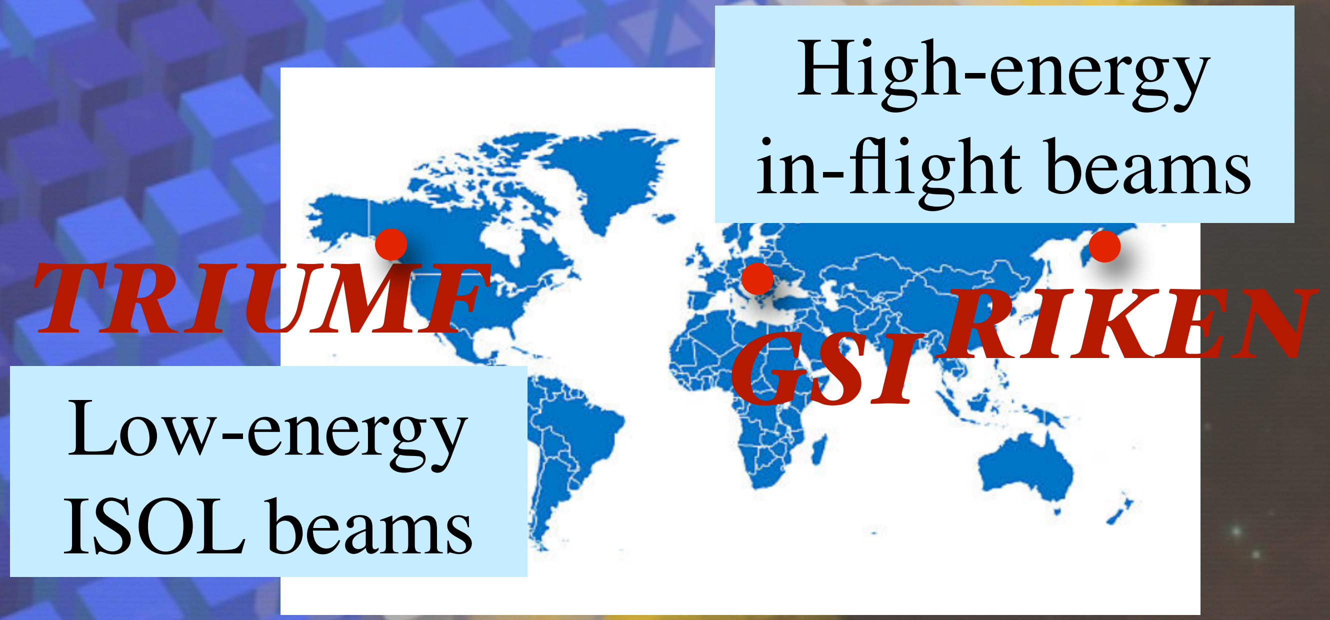
Unveiling exotic features in rare isotopes through direct reactions

R. Kanungo

TRIUMF, Canada



Robert in Canada

Advisory Committee on TRIUMF

Comité consultatif de TRIUMF

Membership List / Liste des membres
(August 2007)

Chair / Président
Dr. Robert V.F. Janssens
Physics Division
Argonne National Laboratory

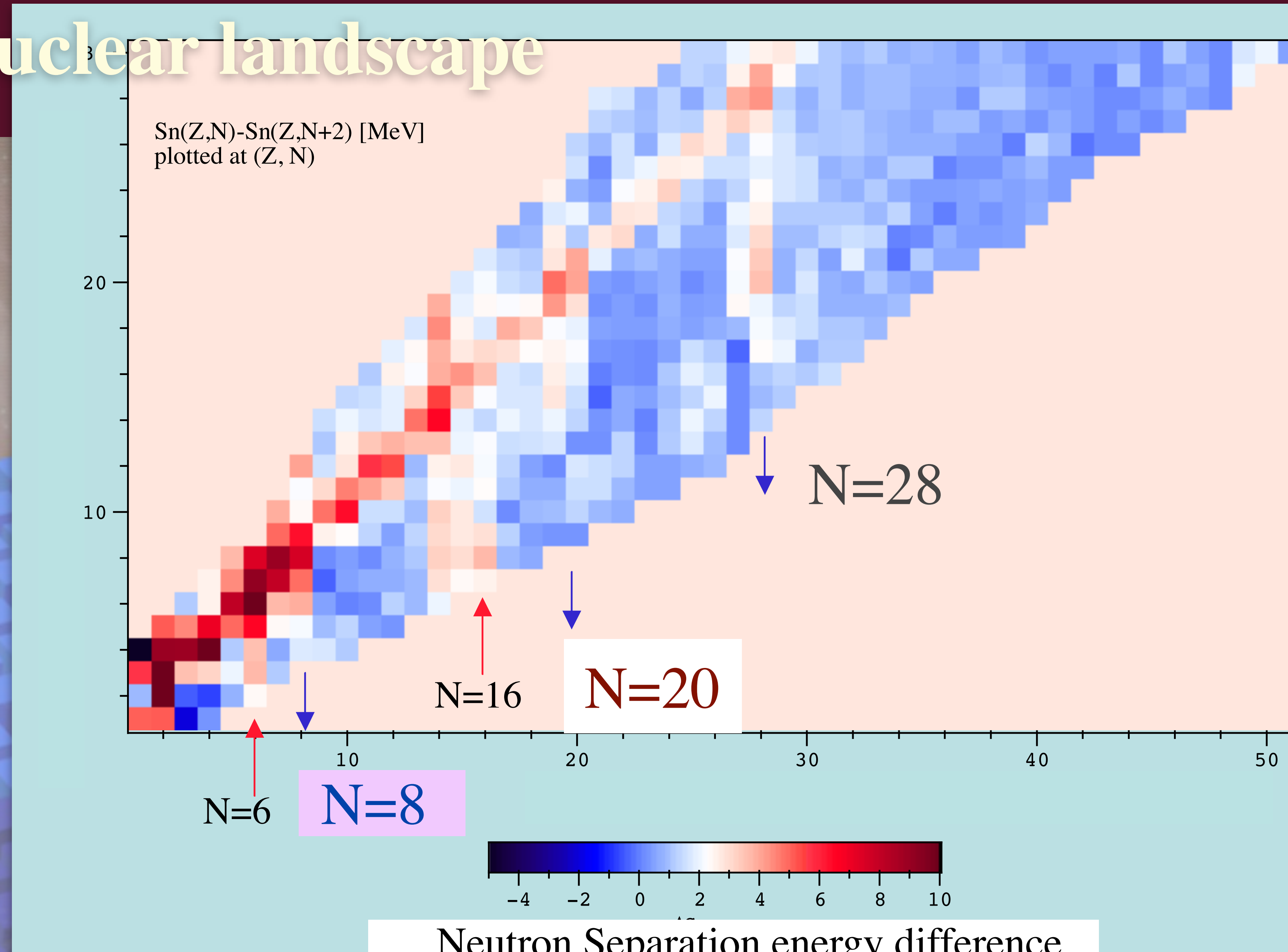
Chair of TRIUMF International Advisory Committee
2007 - 2010

Robert played a major role in supporting and advancing rare isotope beam science in Canada

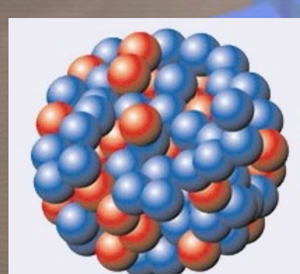
\- Thank you -

The exotics in the nuclear landscape

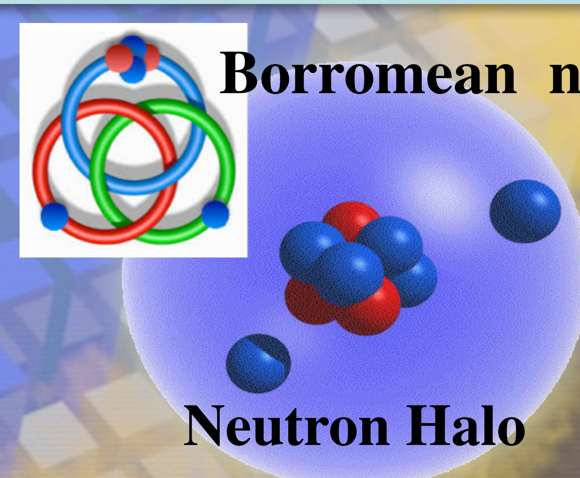
- Weak binding
- Nuclear force
  (3NF, Tensor force)
- Pairing correlation
- Deformation



Proton Number



Stable Nucleus



Neutron-rich matter

Neutron Number

Nobel Symposium NS 152

NOBEL SYMPOSIA

IOP PUBLISHING PHYSICA SCRIPTA

Phys. Scr. **T152** (2013) 014005 (10pp) doi:10.1088/0031-8949/2013/T152/014005

Tracking changes in shell structure in neutron-rich nuclei as a function of spin

Robert V F Janssens

Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

Quenching of $N = 20$ shell gap

$^{14}C(^{18}O,2p)$

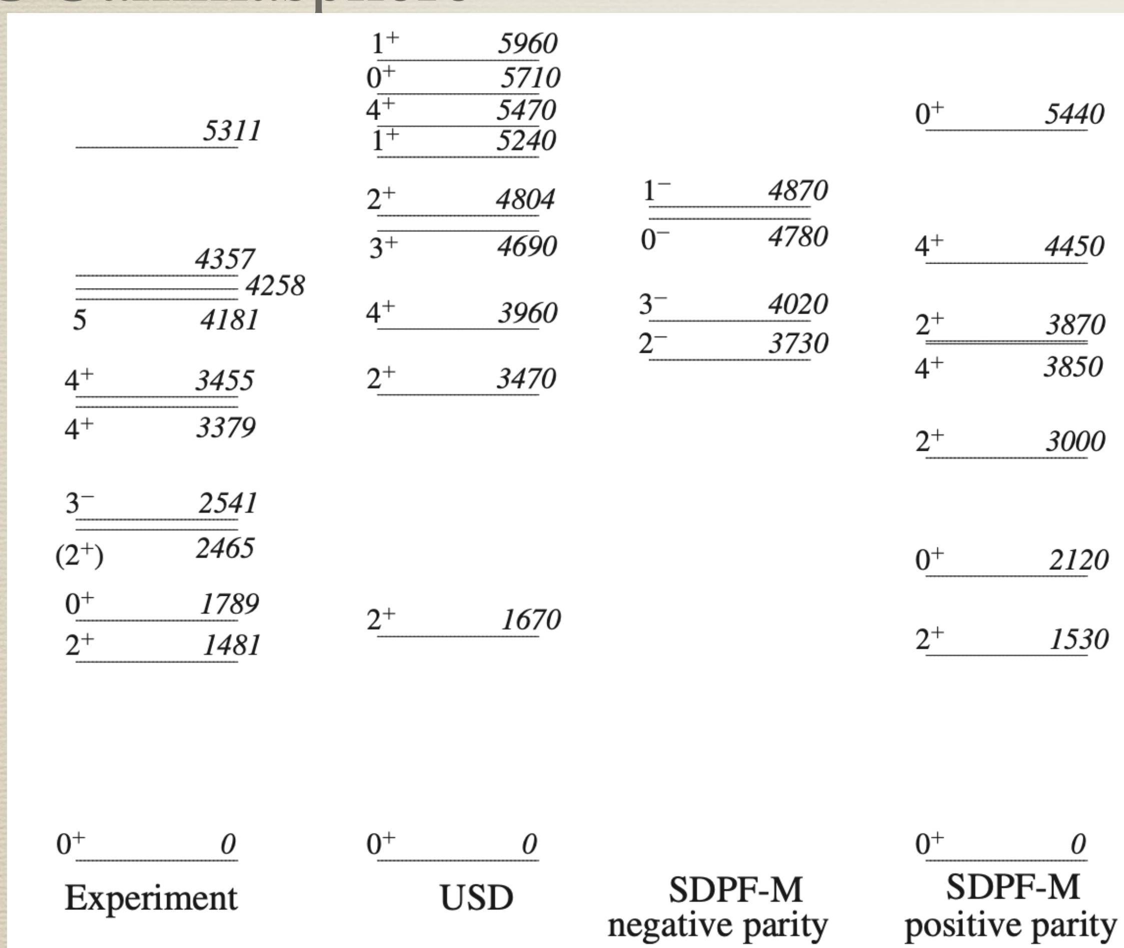
PHYSICAL REVIEW C **82**, 034305 (2010)

Cross-shell excitations near the "island of inversion": Structure of ^{30}Mg

A. N. Deacon,[1,*] J. F. Smith,[2] S. J. Freeman,[1] R. V. F. Janssens,[3] M. P. Carpenter,[3] B. Hadinia,[2] C. R. Hoffman,[4,†] B. P. Kay,[3] T. Lauritsen,[3] C. J. Lister,[3] D. O'Donnell,[2,‡] J. Ollier,[2,‡] T. Otsuka,[5,6] D. Seweryniak,[3] K.-M. Spohr,[2] D. Steppenbeck,[1,§] S. L. Tabor,[4] V. Tripathi,[4] Y. Utsuno,[7] P. T. Wady,[2] and S. Zhu[3]

Fusion evaporation reactions populating high energy, high spin states

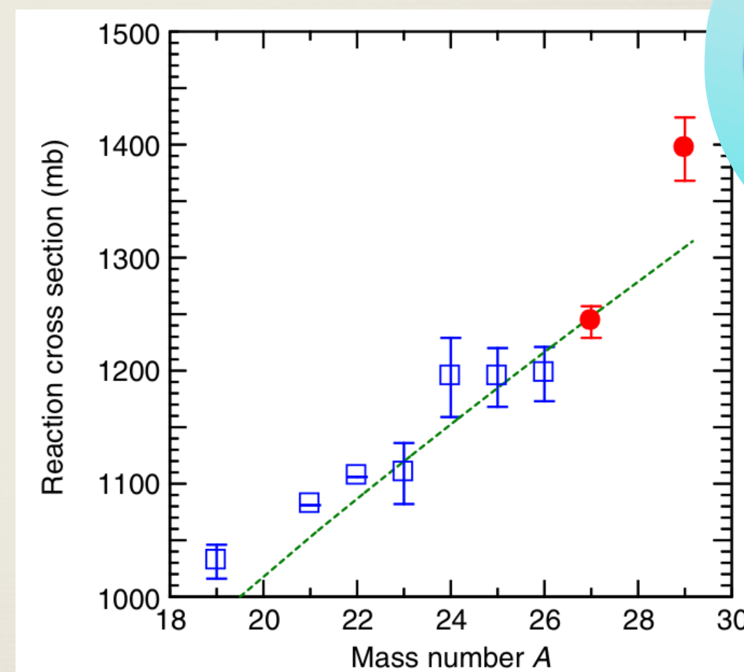
@Gammasphere

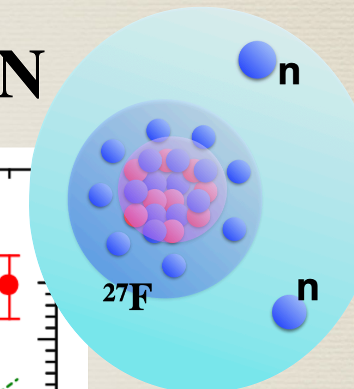


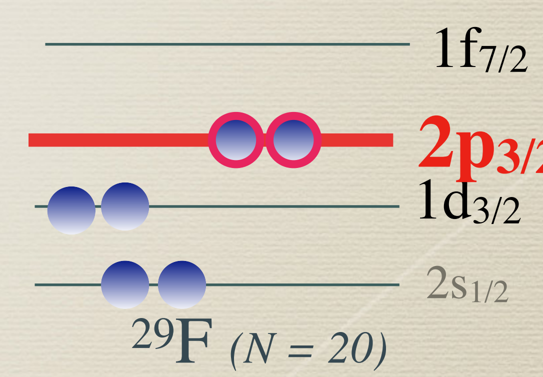
Need excitation across $N = 20$ gap to explain data

$N = 20$ shell gap vanishes

@ RIKEN







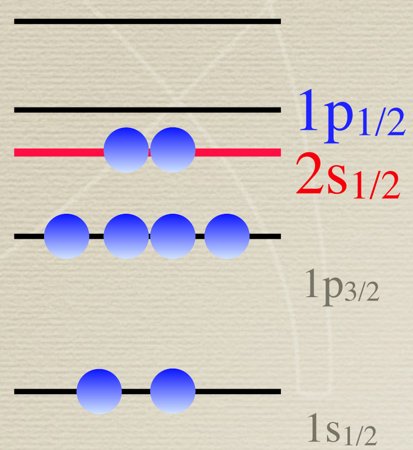
PHYSICAL REVIEW LETTERS **124** 222504 (2020)

S. Bagchi, R.K., Y. K. Tanaka et al.

$N = 20, 28$ shells vanish

$2p_{3/2}$ → Halo

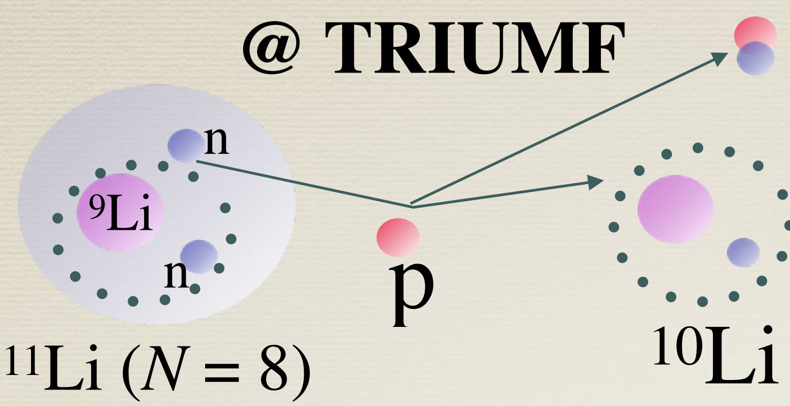
Vanishing of shells & emergence of halos

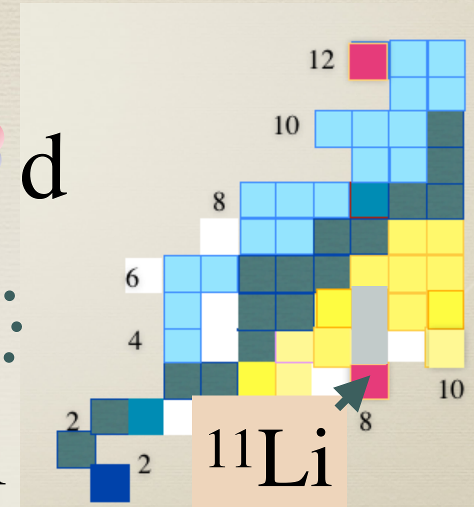


vanishing shell

N = 8

@ TRIUMF

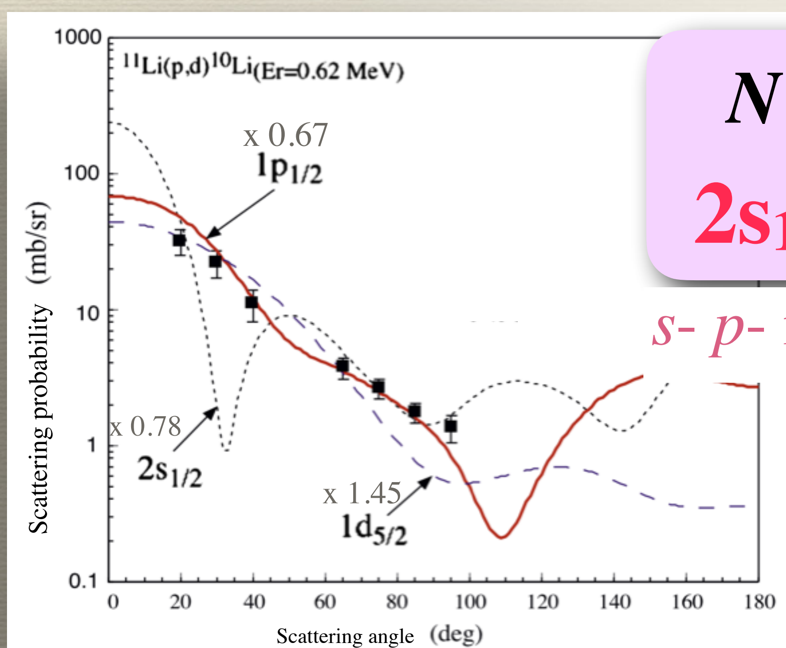




Nucleon **transfer reaction** probability

↓

Nuclear orbital occupancy



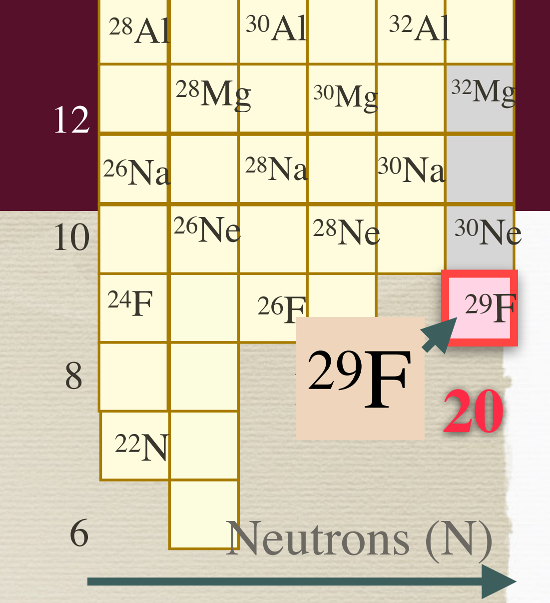
***N* = 8 shell vanishes**

$2s_{1/2}$ → Halo

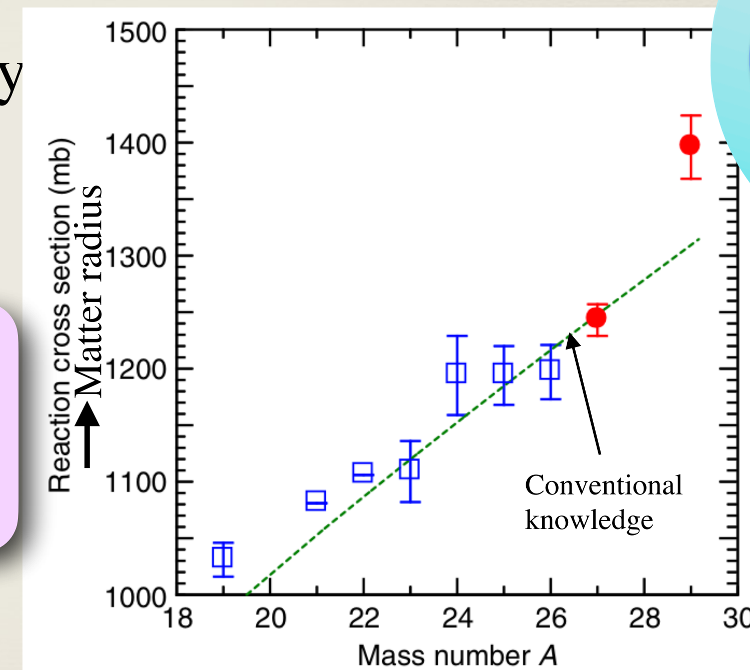
s- p- mixing → correlation

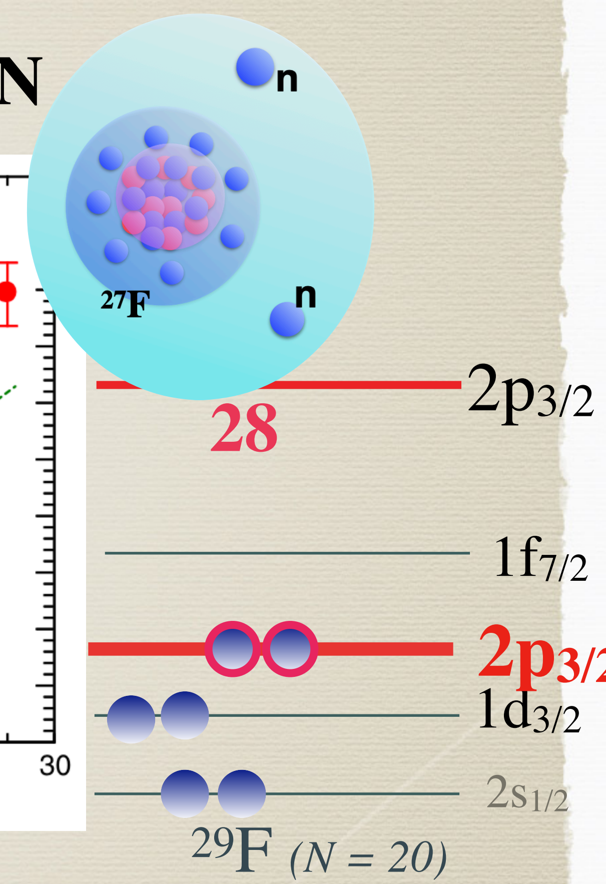
^{11}Li **n($p_{1/2}$) only 33(12) %**

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



@ RIKEN





PHYSICAL REVIEW LETTERS **124** 222504 (2020)

S. Bagchi, R.K., Y. K. Tanaka et al.

***N* = 20, 28 shells vanish**

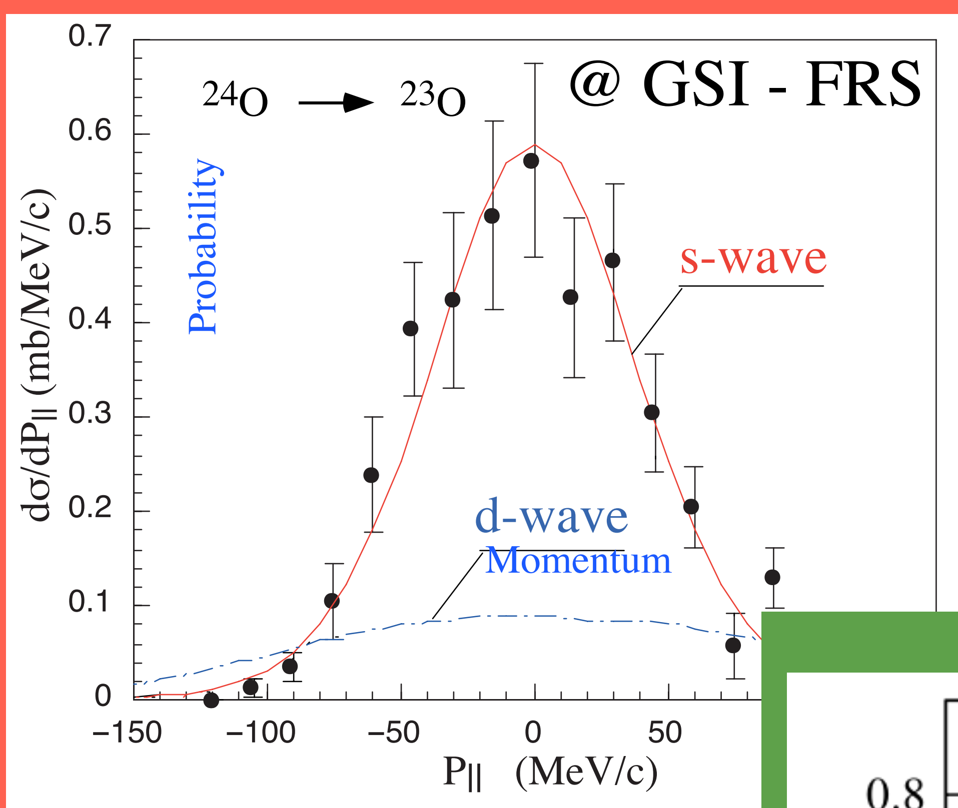
$2p_{3/2}$ → Halo

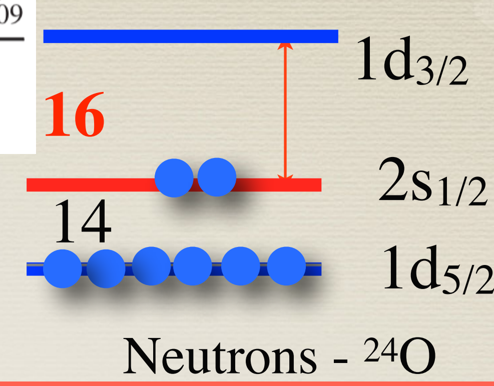
^{24}O new doubly magic @ drip-line

PRL **102,** 152501 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

One-Neutron Removal Measurement Reveals ^{24}O as a New Doubly Magic Nucleus

R. Kanungo et al.





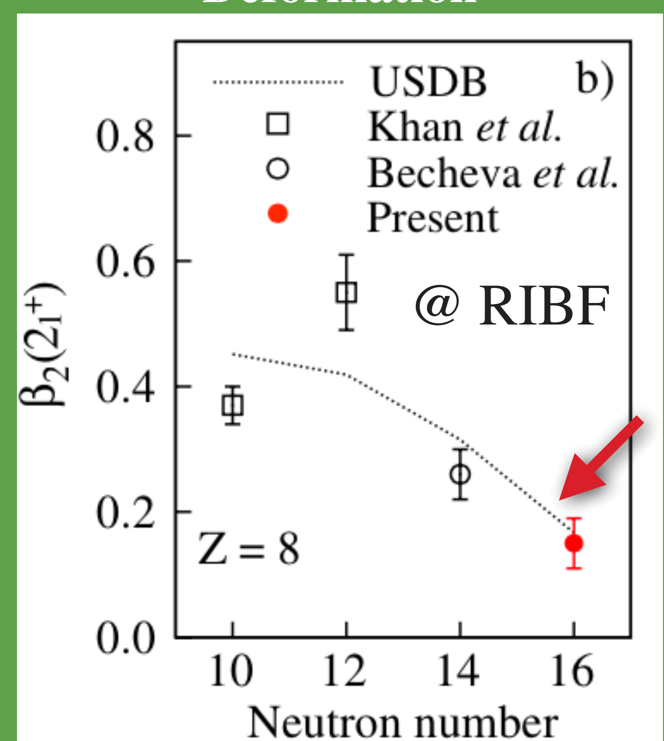
NUCLEAR PHYSICS New & Views :Nature 459 (2009) 1069

Unexpected doubly magic nucleus

Robert V. F. Janssens

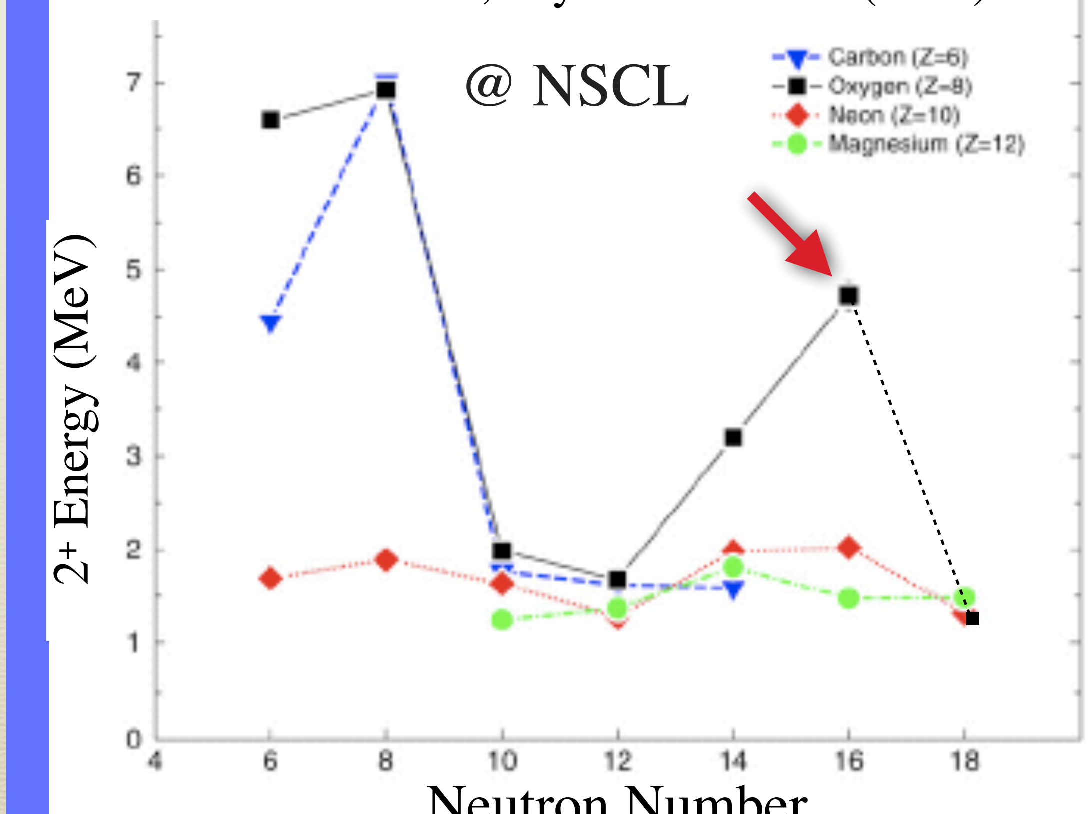
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

Deformation



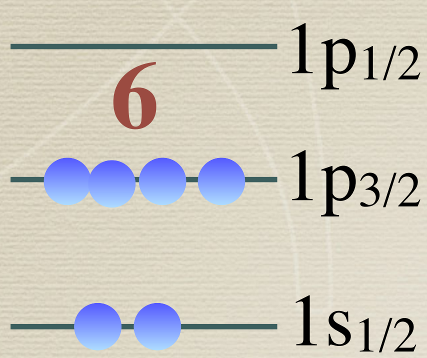
K. Tshoo et al., Phys. Rev. Lett. 109 (2012) 022501

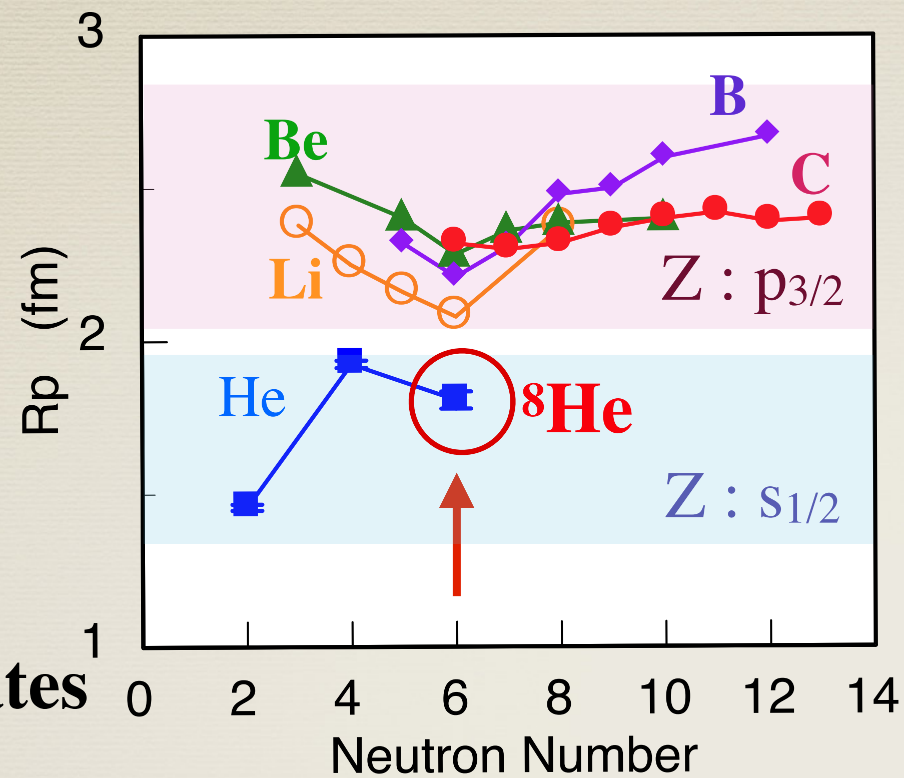
C.R. Hoffman et al., Phys. Lett. B 672 (2009) 17

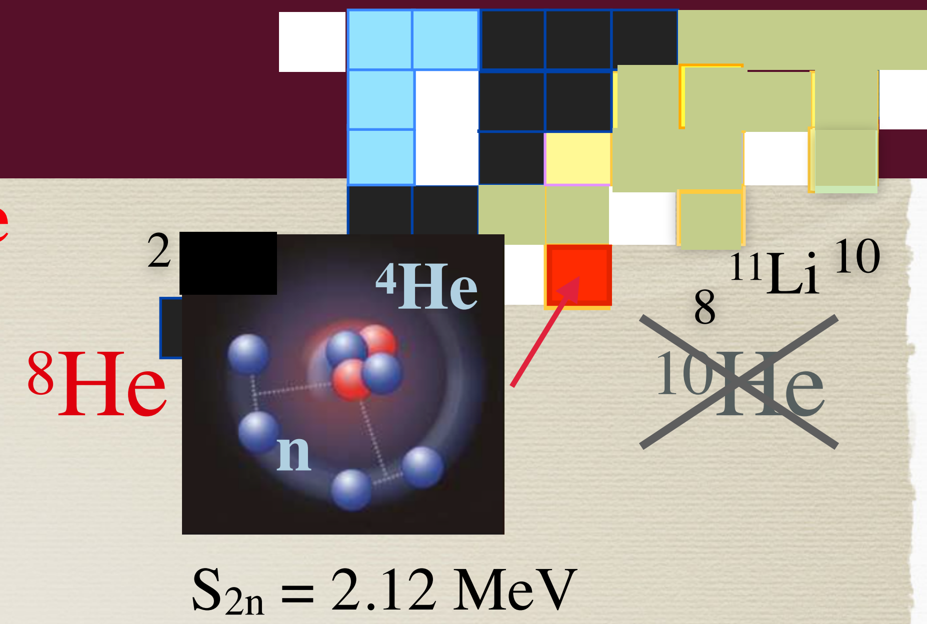


^{8}He : doubly-magic (N = 6)

New doubly magic nucleus ^{8}He







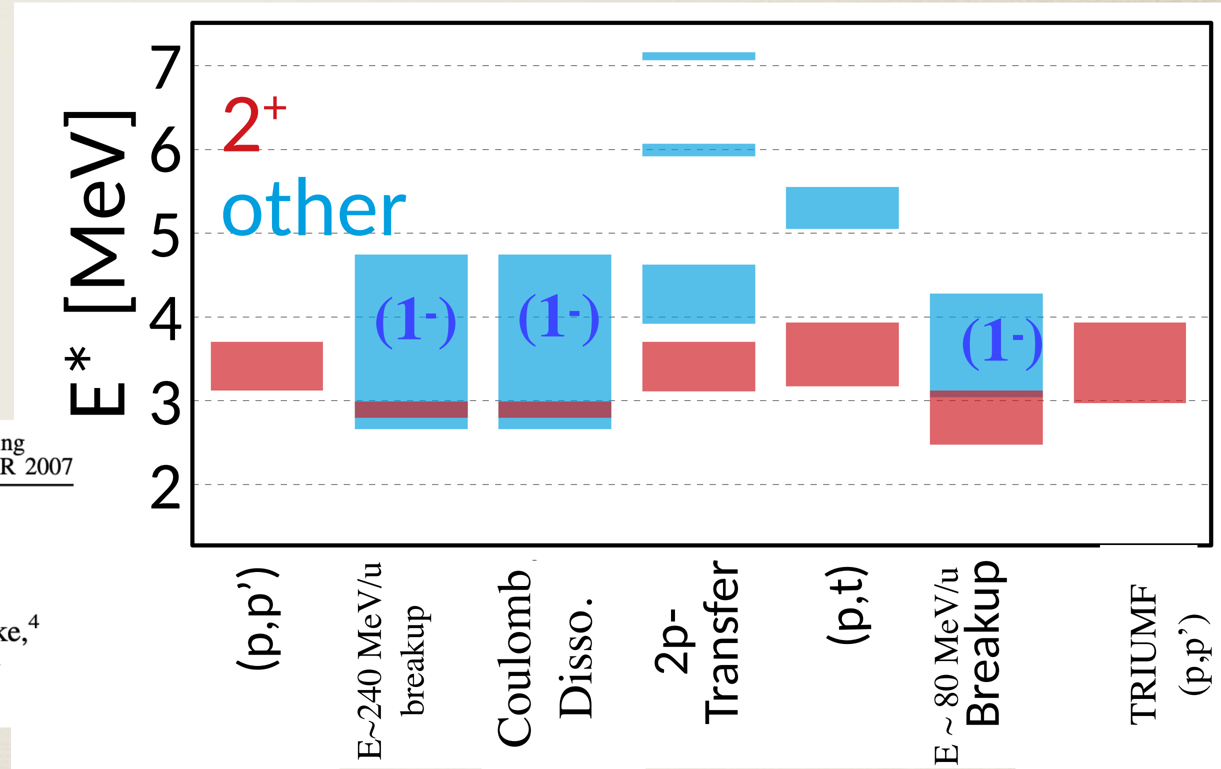
Dip in R_p indicates

N=6 Sub-shell in Z ≤ 5

PRL **99,** 252501 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

Nuclear Charge Radius of ^{8}He

P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4] M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1] M.-G. Saint-Laurent,[3] J.-C. Thomas,[3] and L.-B. Wang[5]

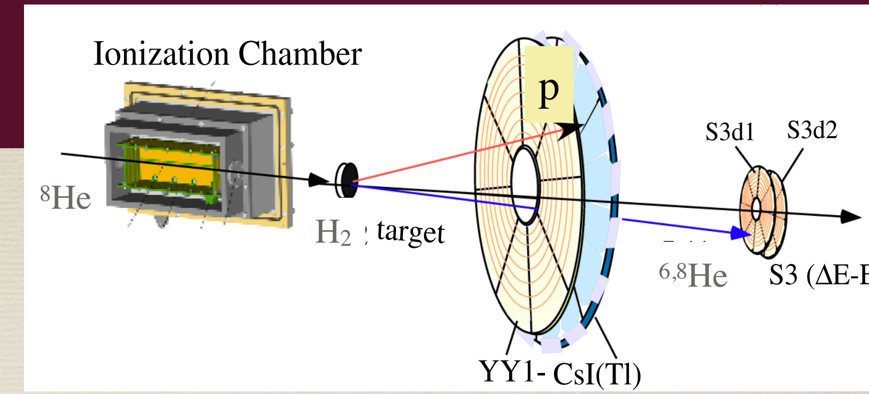


Transfer and inelastic : E(2+) > 3 MeV

Breakup : E(2+) < 3 MeV

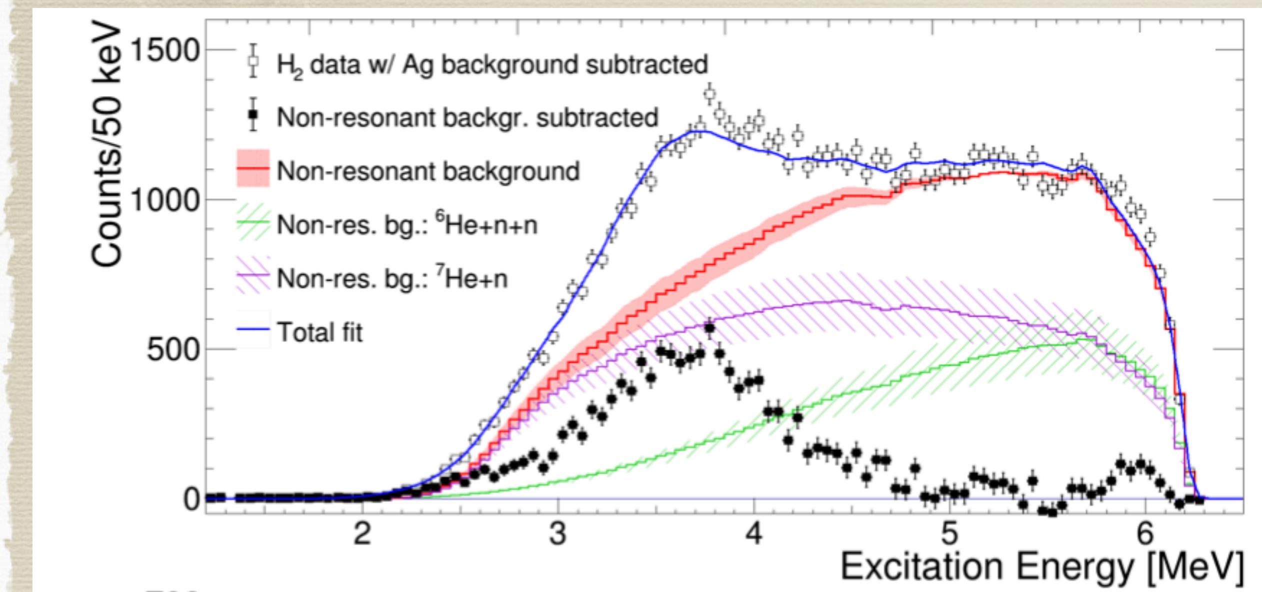
Breakup : Low-energy dipole resonance

^8He : doubly-magic (N = 6) deformed !



^8He(p,p') E/A ~ 7 MeV

New doubly magic nucleus ^8He



M. Holl, R.K., Z.H, Sun *et al*. Phys. Lett. B 822 (2021) 135748

^8He beam ~ 10^4 pps

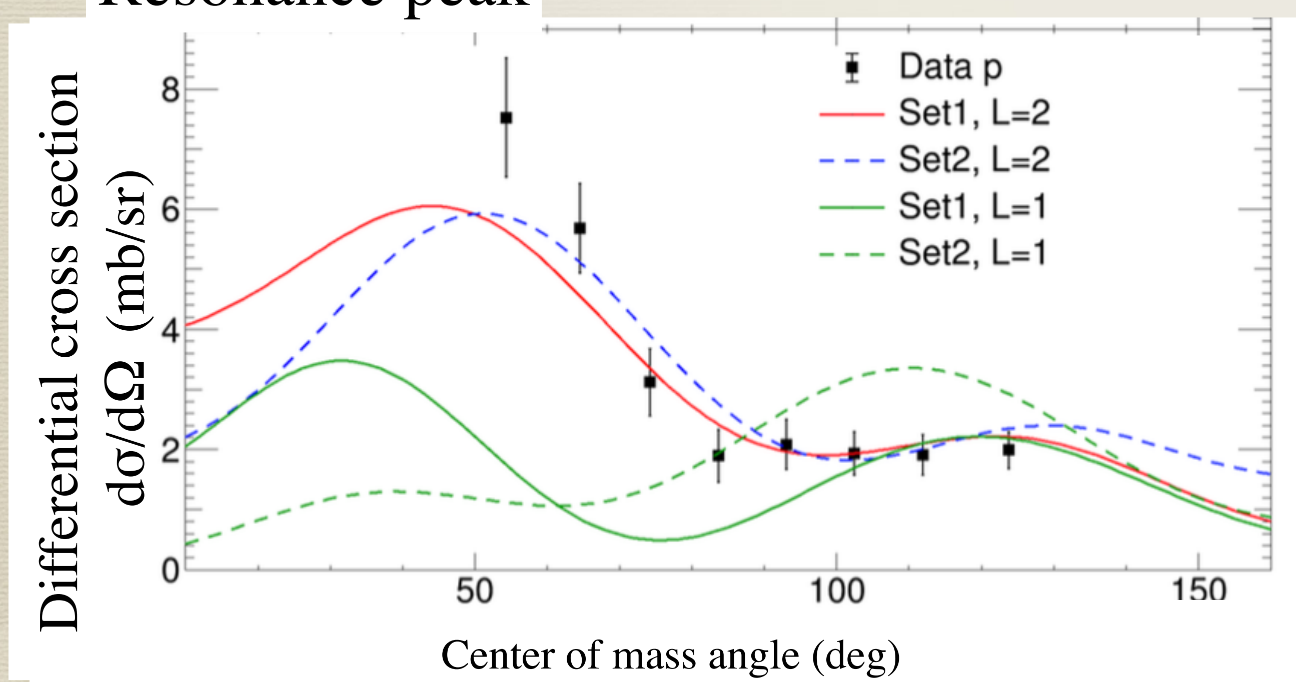
- **Resonance (2^+) shows deformation**

$\beta_2 = 0.40 \pm 0.03$

High Excitation energy ~ Ex ~ 3.5 MeV : closed shell *N* = 6

^8He : spherical in protons and deformed in neutrons

Resonance peak

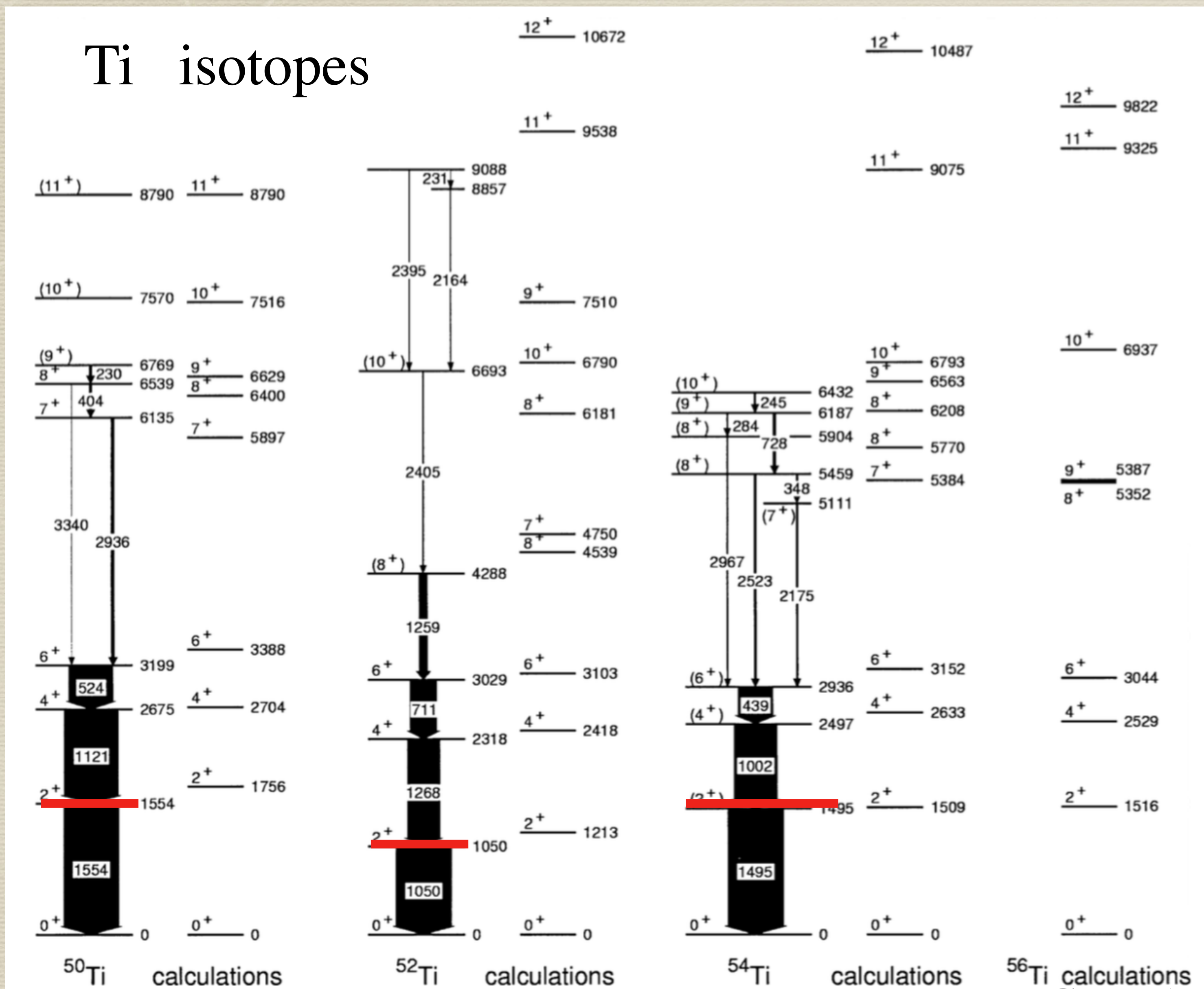


No Core Shell Model with chiral force consistent with experimental observations

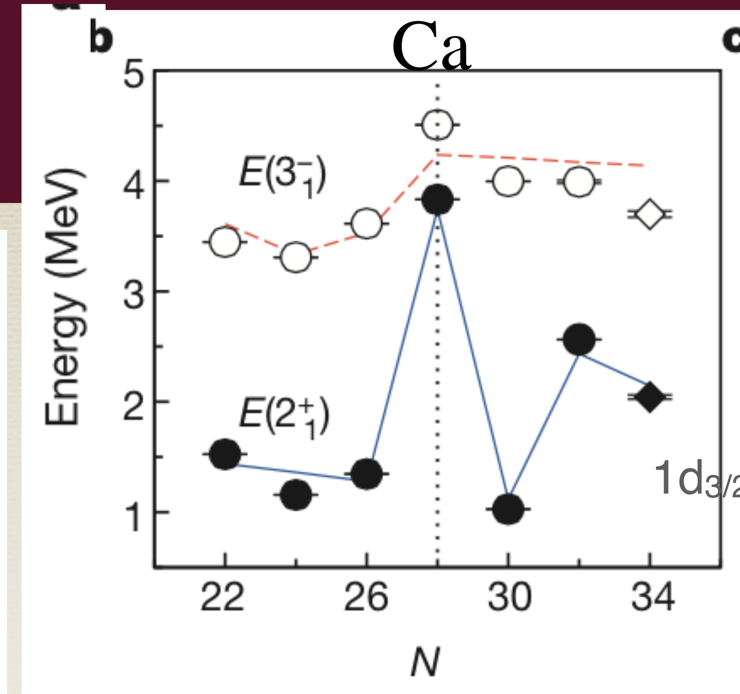
^8He (2^+) : **$Q_n = 6.15$ efm^2**, $Q_p = 0.60$ efm^2

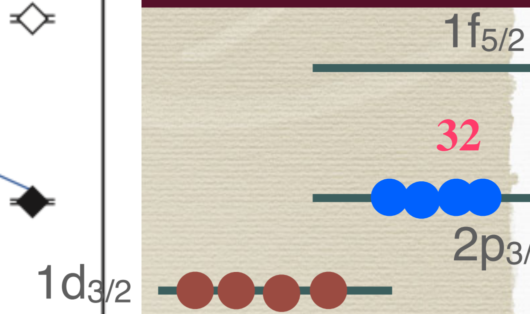
- **Data explained by *l* = 2 excitation**
- **No dipole resonance *l* = 1 excitation**

New magic number $N = 32$



N = 28　　N = 30　　N = 32　　GXPF1

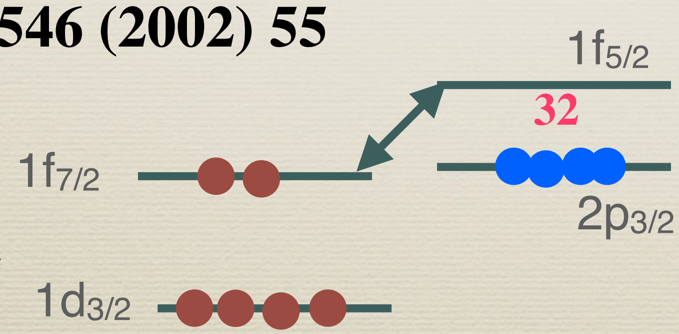




D. Steppenbeck et al. Nature 502 (2013) 207

R.V.F. Janssens et al. PLB 546 (2002) 55

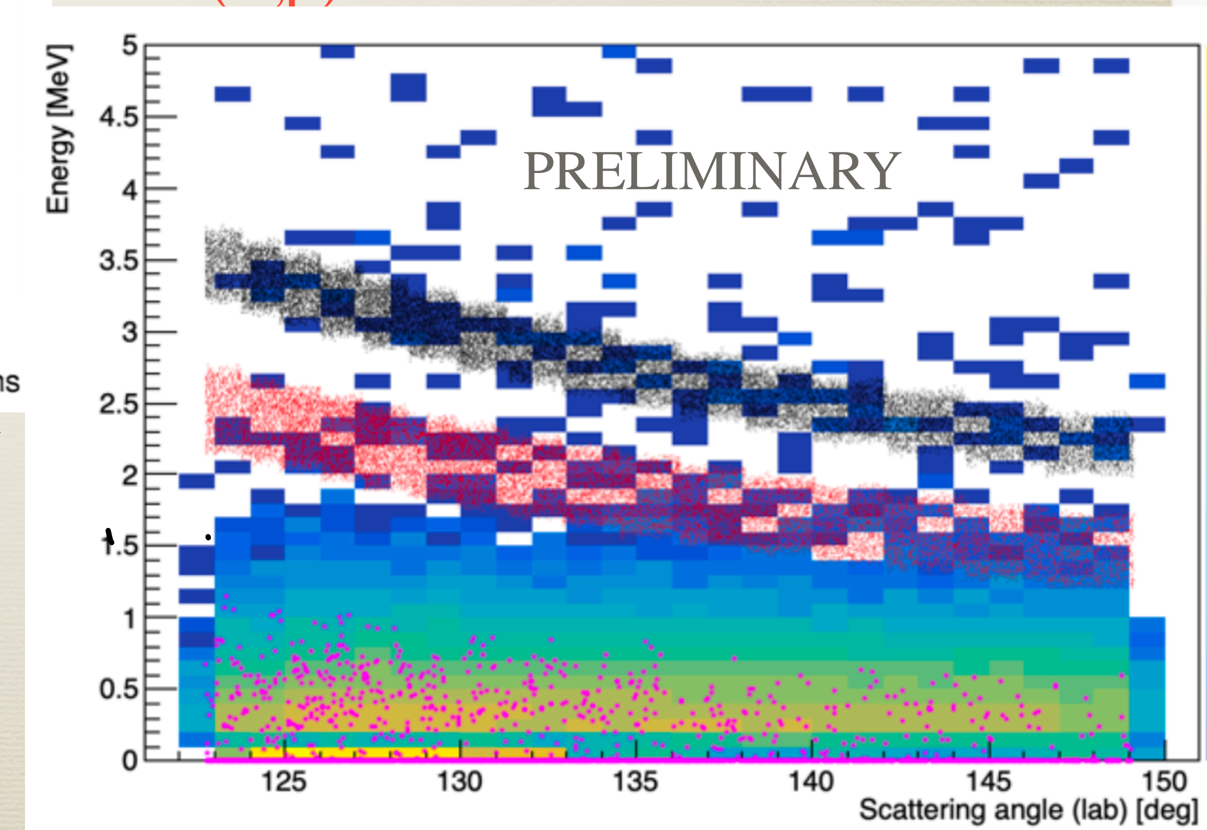
^{54}Ti, $N = 32$ shell gap



$p(f_{7/2})$ - $n(f_{5/2})$ tensor monopole
Attractive interactions
weakening

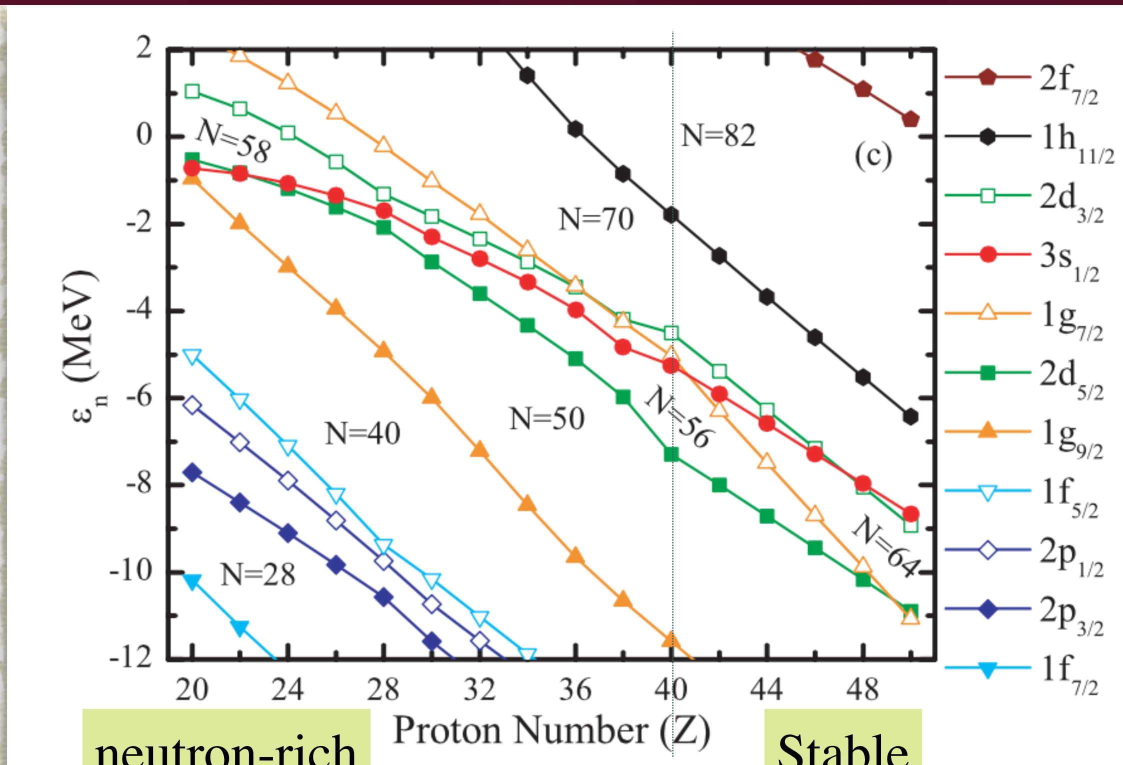
proton　　Neutron

^{50}Ca(d,p)^{51}Ca @ IRIS - TRIUMF



^{50}Ca ~ 400 pps　　S. Ishida *et al.* (in prep.)

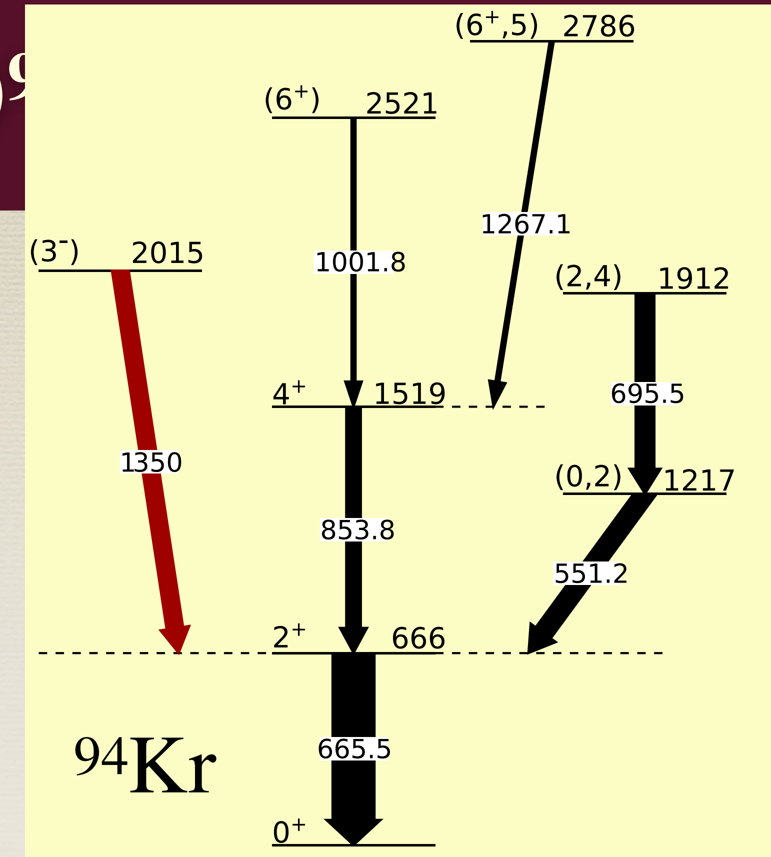
Structure evolution beyond $N = 50$ $^{93}Kr(d,p)^{9}$



Spherical HFB calculation
SkO$_T$ function with tensor term

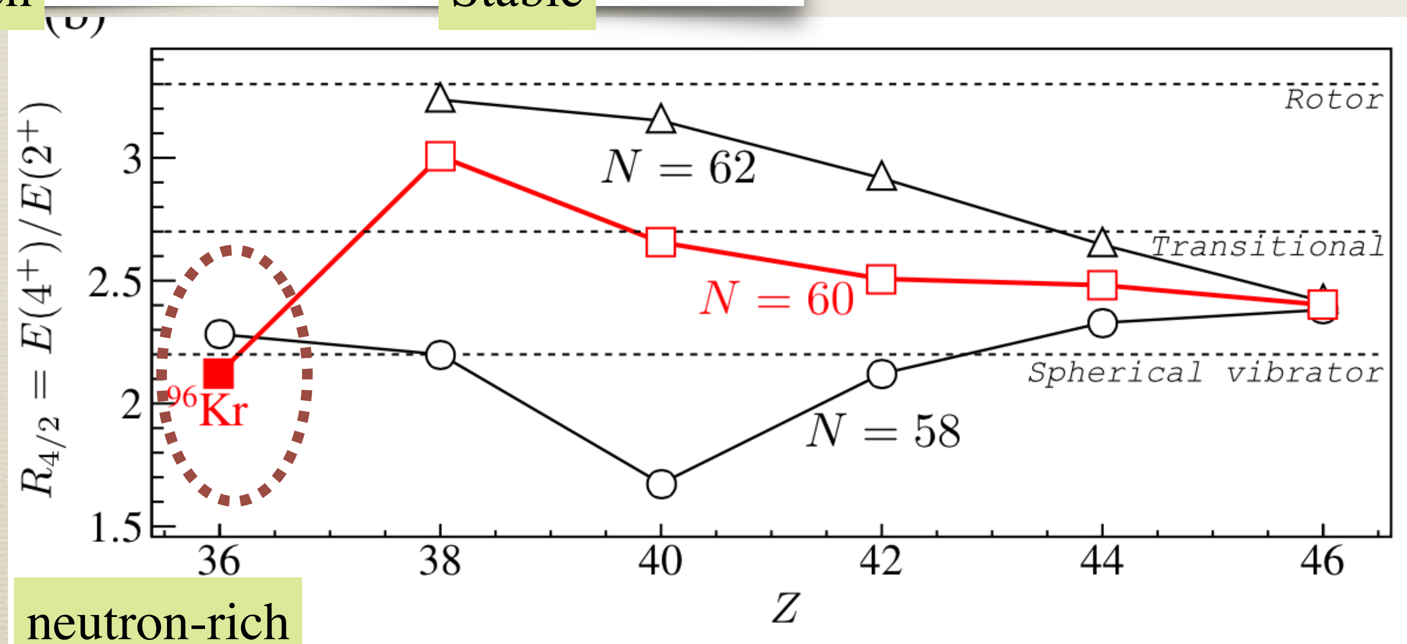
J.A. Winger et al., PRC (2010)

Competing population of the $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ orbitals determine the shape and structure evolution.



R. -B. Gerst et al., PRC (2022)

$^{95}Kr(p,pn)^{94}Kr$ &
$^{94}Kr(p,p)^{94}Kr^*$



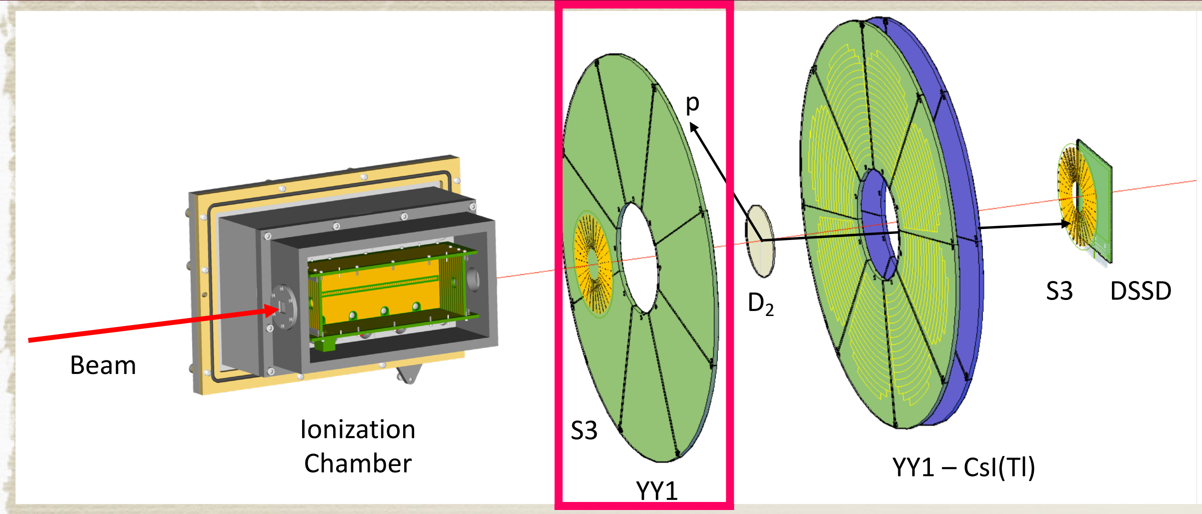
E(4+) / E(2+) trend different in Kr

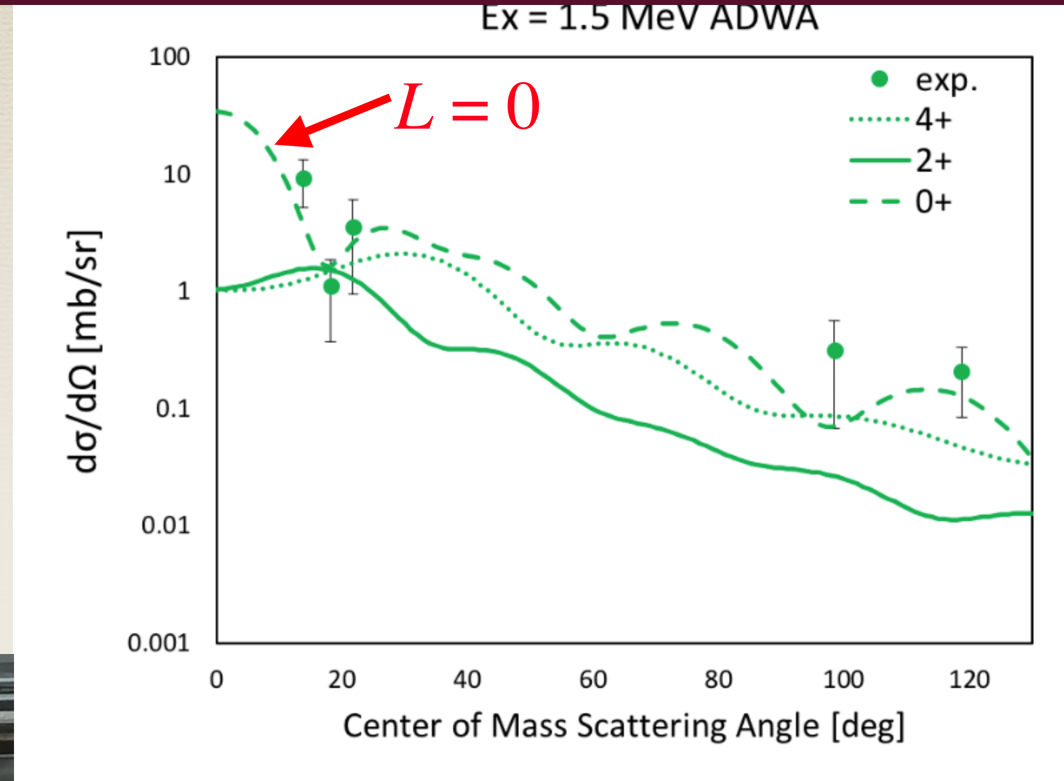
J. Dudouet et al., PRL (2017)

Lack of collectivity at N = 60 in Kr

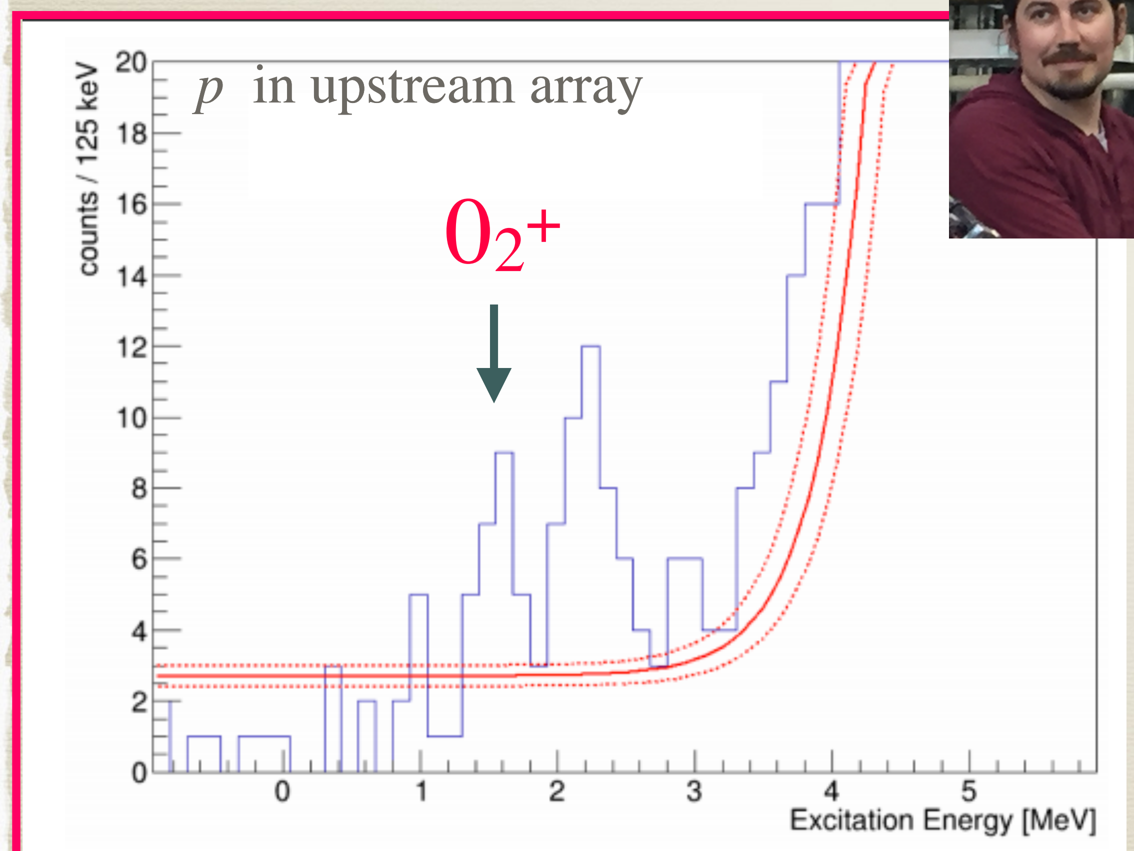
0_2^+ : experimental data needed in ^{94}Kr to assess shape co-existence

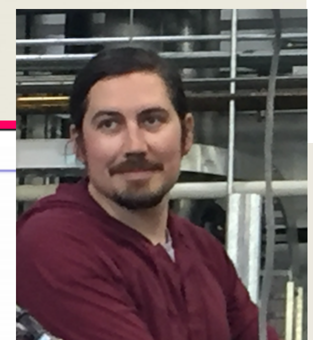
Shape Coexistence in ^{94}Kr ^{93}Kr$(1/2^+)(d,p)^{94}$Kr $(N = 58)$





^{93}Kr beam only 200 pps !





$E_x \sim 1.5$ MeV : $J^\pi = 0^+$

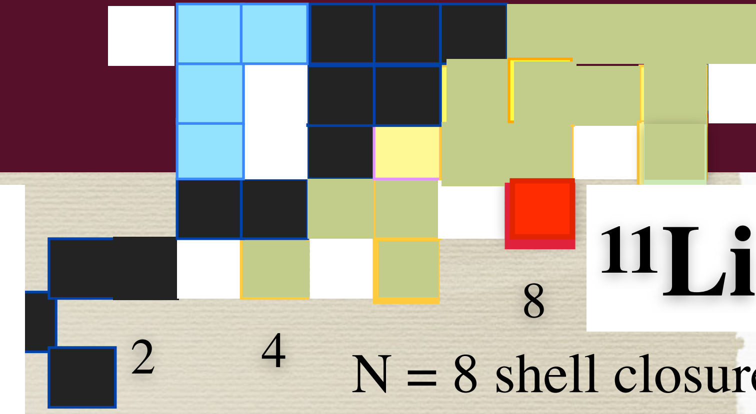
First observation of 0_2^+ state in ^{94}Kr

0_2^+ spherical configuration → stronger overlap with ^{93}Kr$_{gs}$; $S(3s_{1/2}) = 2.14(82)$

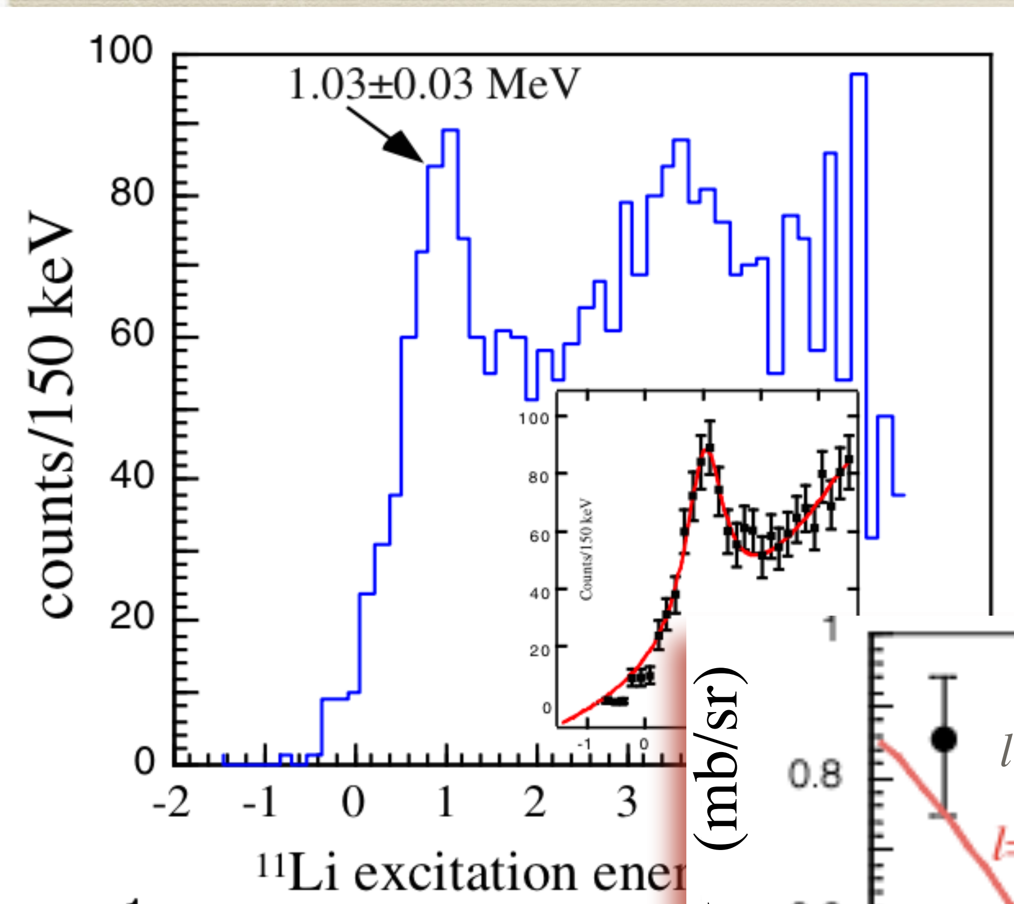
^{94}Kr$_{gs}$ more deformed? → small overlap with ^{93}Kr$_{gs}$; upper limit $S(3s_{1/2}) \sim 0.25$

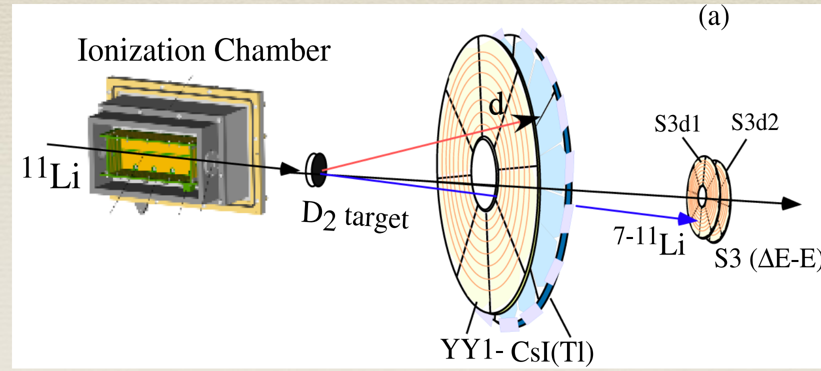
D. Walter, R.K. , M. Holl *et al*. Physics Letters B 862 (2025) 139352

Soft resonances - ^{11}Li Halo excitation



^{11}Li(d,d') $\Delta T=0$

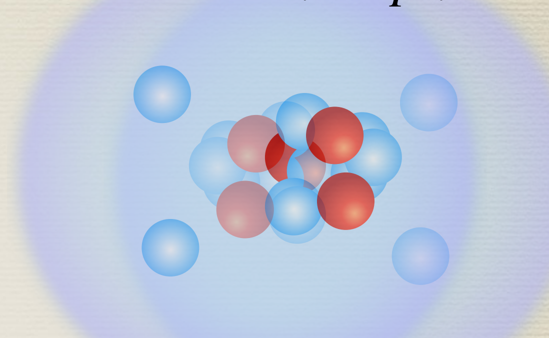




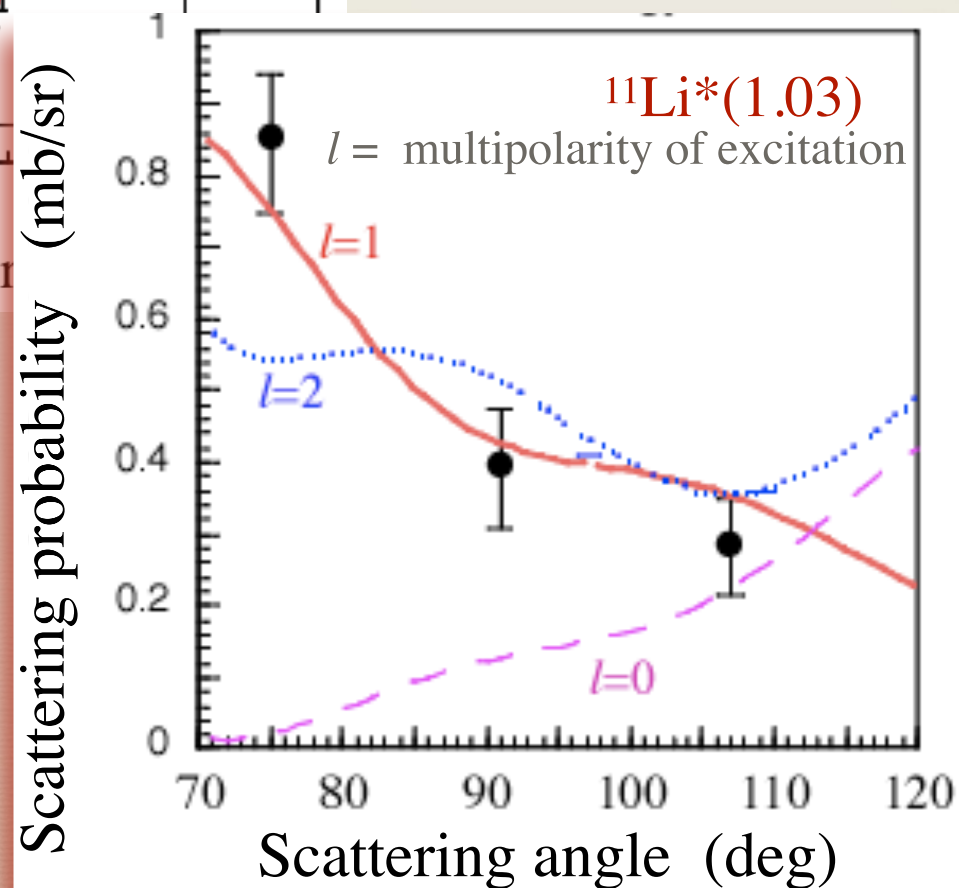
^{11}Li beam ~ 3000 pps

N = 8 shell closure vanishes

$2s_{1/2}$- $1p_{1/2}$- mixing



S_{2n} = 0.36 MeV



E/A= 5 MeV

R.K. et al. Phys.Rev. Lett. 114 (2015) 192502

Isoscalar Soft Dipole Resonance Observed

Low-energy dipole states : ^{64}Ni @ HIγS

S_n = 9.7 MeV

PHYSICAL REVIEW C **109**, 044318 (2024)

E1 & M1 transition measurements by photon scattering (γ,γ')

Low-lying dipole response of ^{64}Ni

M. Müscher,[1,*] E. Litvinova,[2,3,4] R. Schwengner,[5] T. Beck,[3] D. Bemmerer,[5] F. Fiedler,[5] S. W. Finch,[6,7] U. Friman-Gayer,[8] S. Hammer,[5] J. Isaak,[9] R. V. F. Janssens,[7,10] A. R. Junghans,[5] N. Kelly,[11] F. Kluwig,[1] Krishichayan,[6,7] S. E. Müller,[5] O. Papst,[9] K. Römer,[5] D. Savran,[12] M. Scheck,[11] T. Schüttler,[1] J. Sinclair,[11,13] T. Szücs,[5,†] W. Tornow,[6,7] A. Wagner,[5] J. Wilhelmy,[1] and A. Zilges[1]

(θ°,ϕ°)

(90°,90°) : E1 detector

(90°,0°) : M1 detector

$$\Sigma_{hv} = \frac{W(90^\circ,0^\circ) - W(90^\circ,90^\circ)}{W(90^\circ,0^\circ) + W(90^\circ,90^\circ)}$$

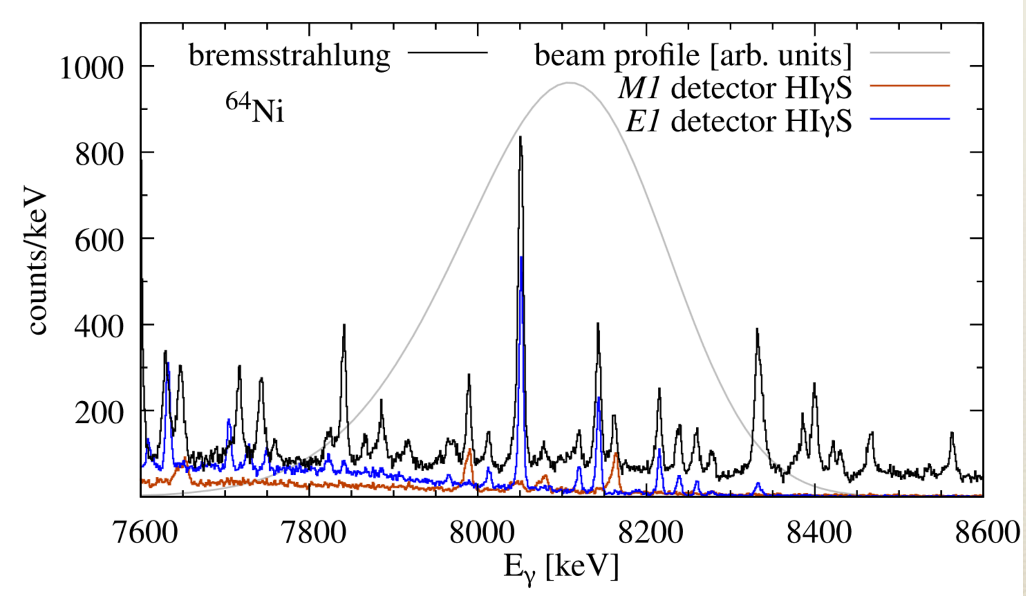
$\Sigma_{hv} = +1$ M1

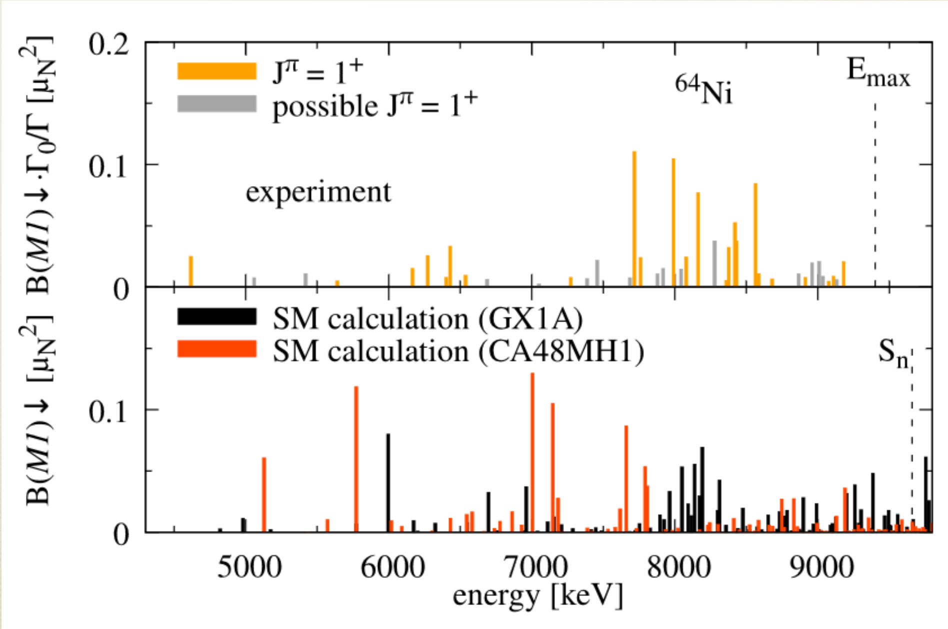
$\Sigma_{hv} = -1$ E1

Two types of photon beams used

Continuous energy Bremsstrahlung @ γELBE - HZDR

Quasi monoenergetic linearly polarized @ **HIγS - TUNL**





- ✳ Strong E1 peak seen below S_n
- ✳ M1 transitions are small

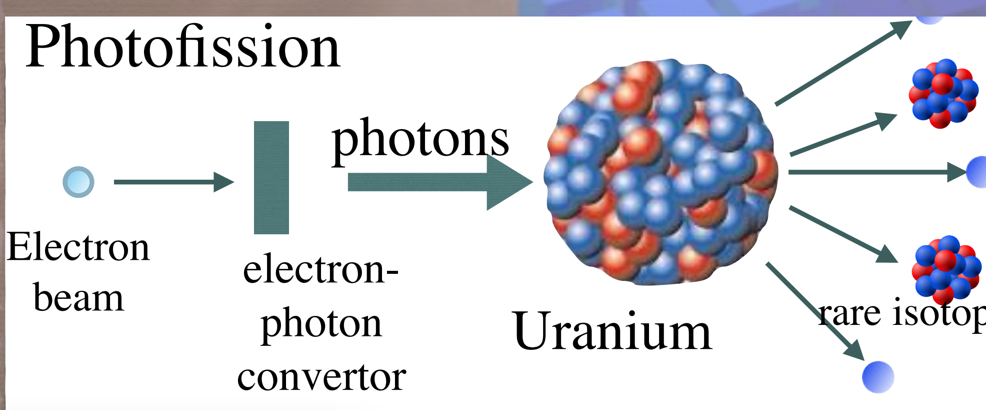
Data deviate from shell model predictions

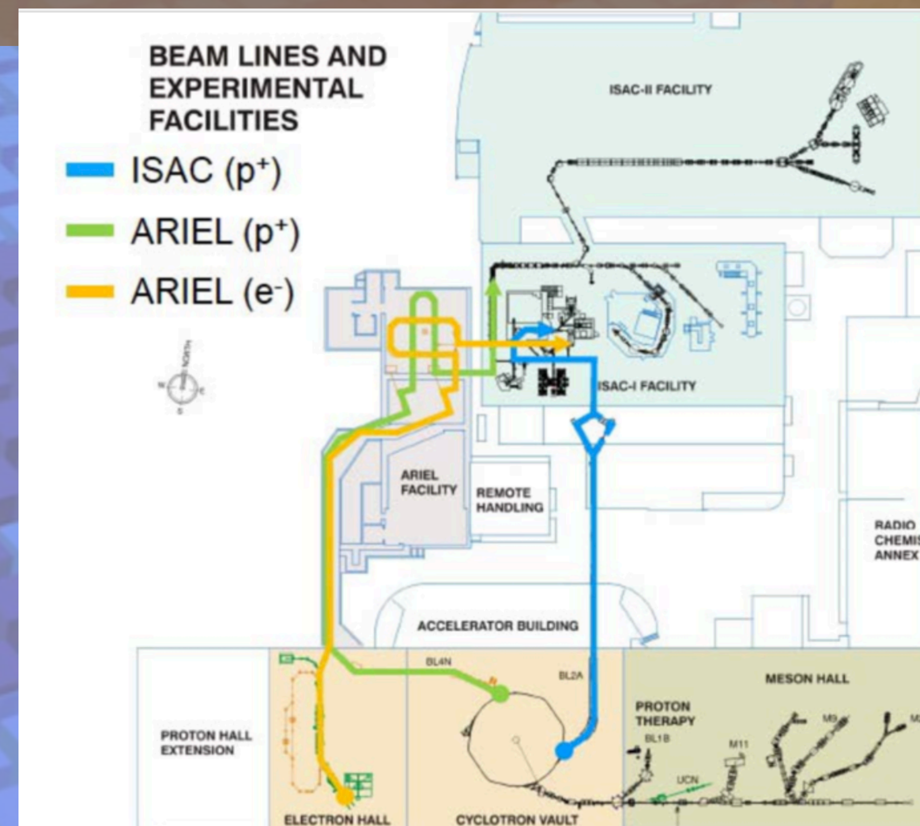
Summary and outlook

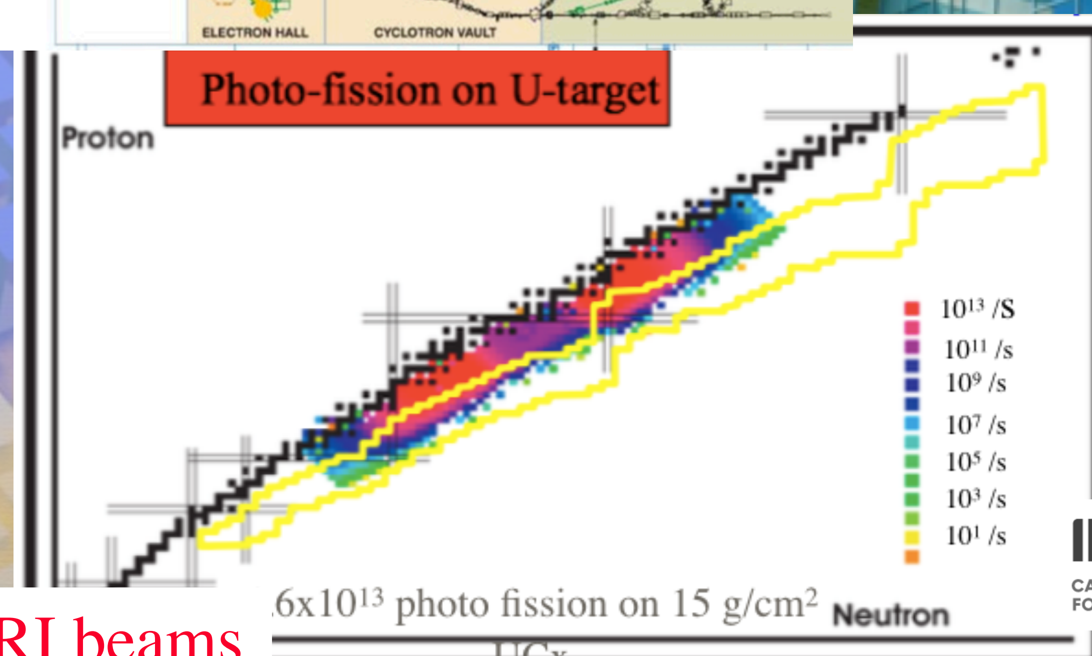
Reactions at different energies unevil new exotic nuclear & transformation of nuclear shells - challenging our knowledge of the nuclear force.

New complementary facilities in North America open

FRIB @ MSU, USA
ARIEL @ TRIUMF, Canada







INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

ARIEL @ TRIUMF

World's only facility with 3 simultaneous RI beams
(2 *p*-induced + 1 photofission)

Wishing you a Happy & Relaxed Retirement
with lots of fun & free time to do the things you love

Thank you Robert from everyone at TRIUMF for your invaluable contributions to the laboratory and in the field of nuclear physics

Enjoy continuing experiments
with lobster !