Spins, moments, radii:

probing changes in the nuclear shell structure

Gerda Neyens
for following 'moments and radii' collaborations at ISOLDE-CERN:

Existing:

(1) COLLAPS = COLinear LAser Spectroscopy beamline + β-NMR — I, g, Q, 10^3/s
(Mainz, Leuven, ISOLDE, …) — $\delta\langle r^2\rangle$ 10^6/s

(2) COMPLIS = COllaboration for spectroscopy Measurements using a Pulsed Laser Ions Source — I,g,Q, $\delta\langle r^2\rangle$ 10^7/s
(Orsay, Mainz, Montreal, Grenoble)

(3) In-source laser spectroscopy — I,g, $\delta\langle r^2\rangle$ 10/s !
(Leuven, Liverpool, Orsay, Troisk, Mainz, ISOLDE)

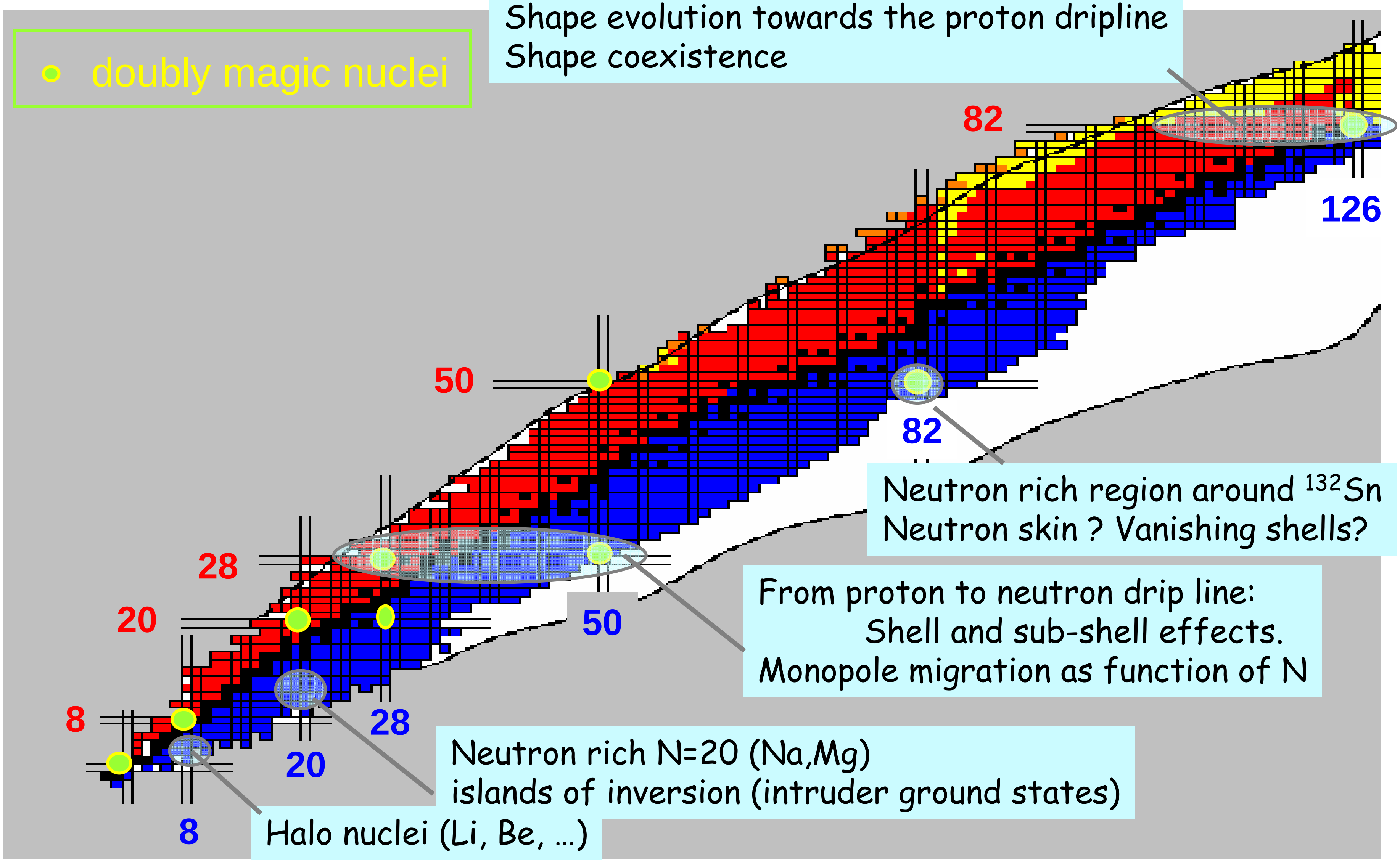
(4) NICOLE = Low Temperature Nuclear Orientation + β-NMR — I, g, Q 10^4/s
(Leuven, Bonn, Weismann, Oxford)

Near future:

(5) Using post-accelerated beams at REX-ISOLDE — ps-states, μs isomers
(Bonn, Munchen, Madrid, Orsay, Sofia, Leuven, …) — g 10^5/s

(6) Laser spectroscopy of light ions in a Paul trap — $\delta\langle r^2\rangle$ 10^4/s
(GSI, Tubingen, Mainz, …)

The strength of ISOLDE: complementary tools to investigate moments and radii of all kinds of elements towards the extremes



Charge radii:

probing halo properties of nuclei

Two-photon resonance laser spectroscopy: pioneered at TRIUMF-CANADA

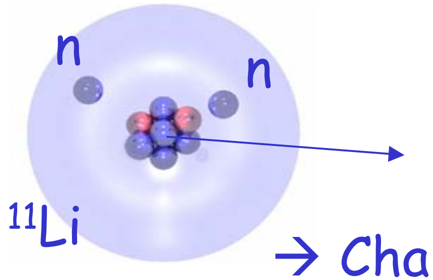
G. Ewald et al., Phys. Rev. Lett. 94, 039901 (2004)

R. Sanchez et al., Phys. Rev. Lett. (2005) submitted

Laser spectroscopy in a MOT: pioneered at Argonne National Laboratory

L.-B. Wang *et al.*,Phys. Rev. Lett. **93**, 142501 (2004)

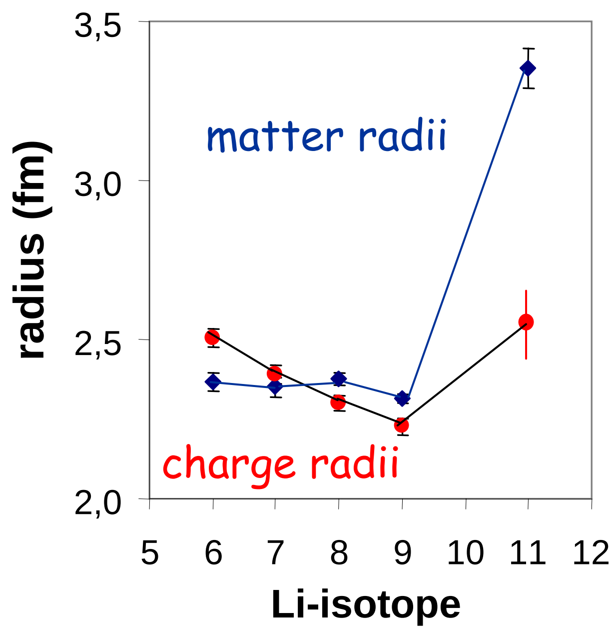
→High precision experiments !



Halo Model:

Only the core is charged

→ Charge radius of halo nucleus
= to charge radius of core nucleus ?



2002: Indirect via elastic scattering of ^{11}Li on proton target
(GSI-Darmstadt) EPJA15, 27 (2002)

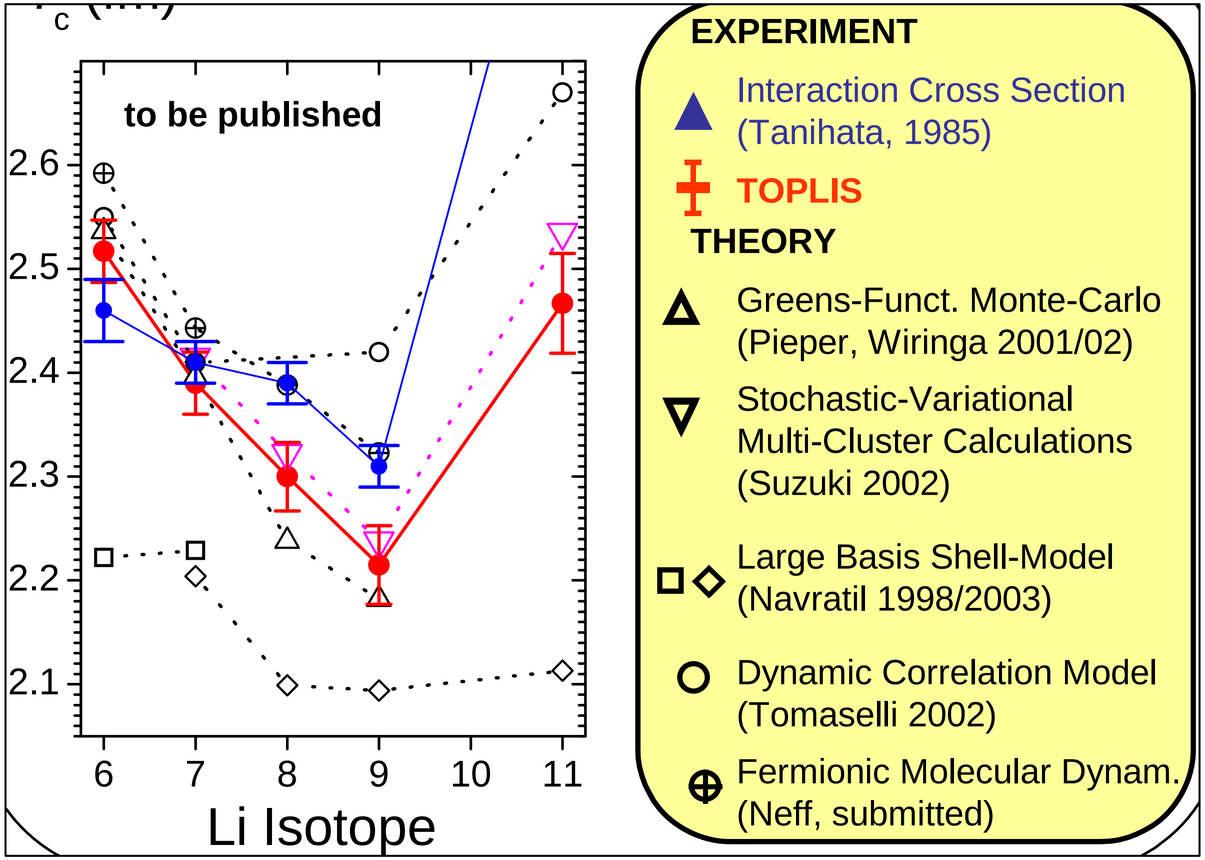
2004: Direct via two-photon laser spectroscopy
(GSI, TRIUMF-CANADA, W. Nörthershäuser et al.)
→ **improved precision to 0.04 fm !**

Charge radii:

probing halo properties of nuclei

Two-photon resonance laser spectroscopy: charge radii of halo nuclei

G. Ewald et al., Phys. Rev. Lett. 94, 039901 (2004)
R. Sanchez et al., Phys. Rev. Lett. (2005) submitted



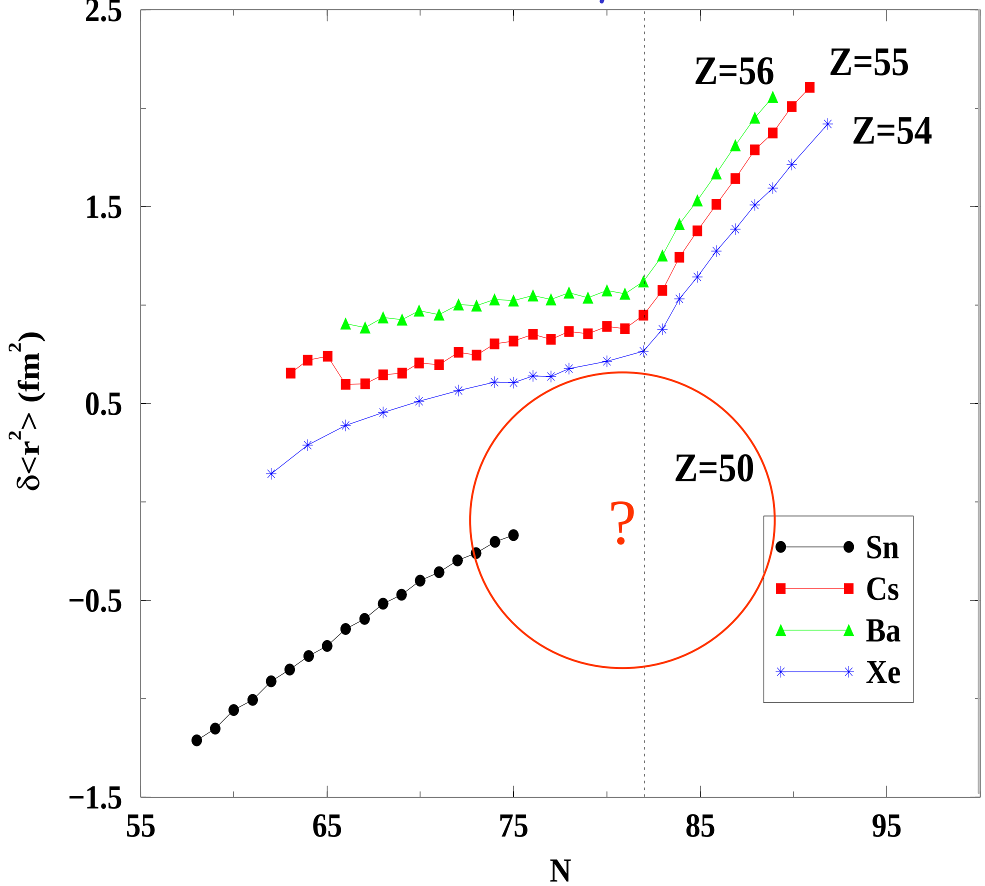
High-precision:
needed as a stringent test of newly-developed nuclear models !

Charge radii:
probing deformation properties of nuclei

COMPLIS: changes in the mean square charge radii of Sn-isotopes beyond ^{132}Sn

F. Leblanc et al., Nucl. Phys. A734, 437 (2004)
F. Leblanc et al., Phys. Rev. C, 72, 034305 (2005)

→ onset of deformation beyond N=82 for Z=54,55,56



Related work from this group:
Te-chain (Z=52)
N=72 (stable) to N=84 !
(data analysis in progress)

Future : 110-120Te
(N=58 to the stables)

Charge radii:

probing deformation properties of nuclei

COMPLIS: changes in the mean square charge radius of Sn-isotopes beyond ^{132}Sn

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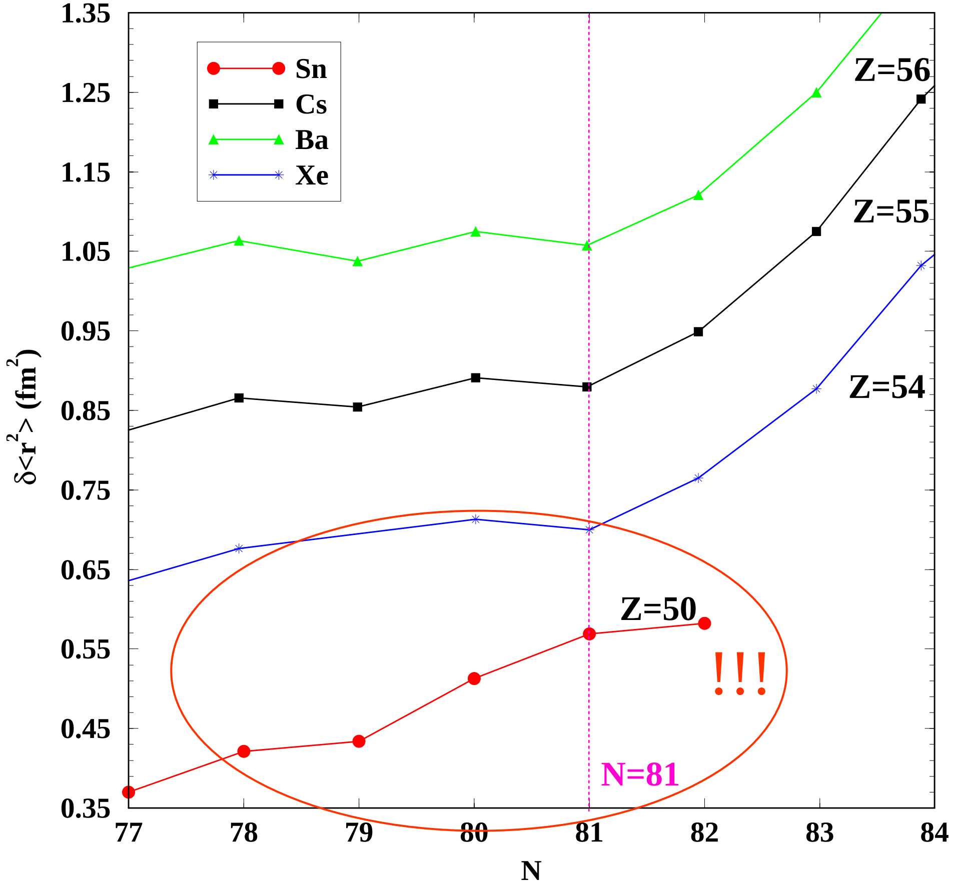


Conclusions:

(1) From measured Q-moments:
Z=50: a good proton shell closure
deformation $\beta < 0.04$

(2) Does a kink appear at ^{132}Sn ?
→ emergence of a neutron skin ??

Charge radii, magnetic and quadrupole moments: single particle and deformation properties of nuclei

In-source laser spectroscopy: pioneered at ISOLDE-CERN

probing the most exotic (heavy) elements

charge radii, magnetic moments

e.g ^{183}Pb at 10/s at resonance !!! A. Andreyev et al. EPJA14, 63 (2002)

H. De Witte, Ph. Thesis K.U. Leuven, 2004 and in preparation

high sensitivity → magnetic moments of very neutron rich nuclei !

e.g. Cu isotopes up to ^{77}Cu

magnetic moments

no charge radii (less accurate)

L. Weissman et al., PRC 65, 024315 (2002)

Magnetic and quadrupole moments:
stringent test and input for nuclear models

NICOLE: on-line Low Temperature Nuclear Orientation + β-NMR

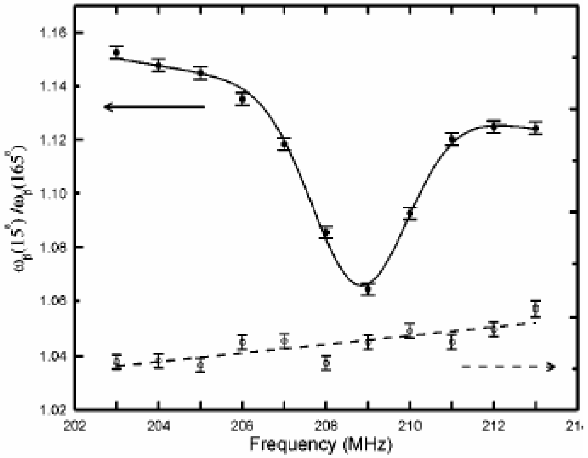
g-factor of ^{69}Cu ($3/2^-$, 3 min) J. Rikovska et al., Phys. Rev. Lett. 85, 1392 (2000)

^{71}Cu ($3/2^-$, 19 sec) K. Van Esbroeck, Diploma Thesis, K.U. Leuven, 2000

^{59}Cu ($3/2^-$, 82 sec) V. Golovko et al., Phys. Rev. C70, 014312 (2004)

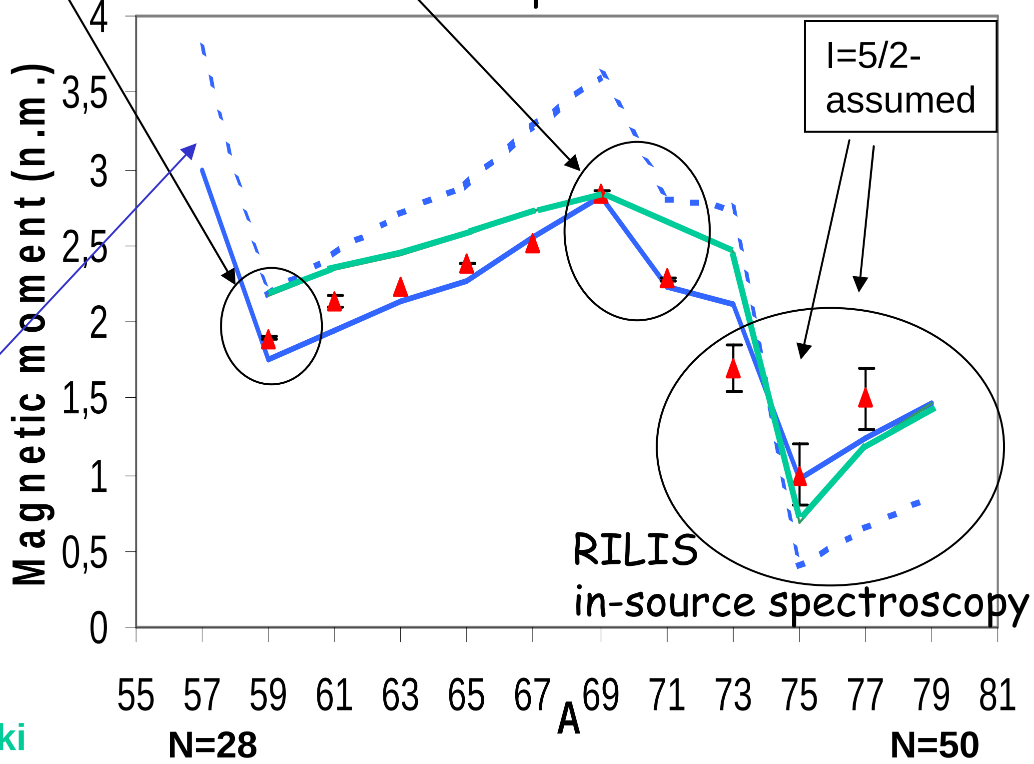
→ to go to drip lines: need β-NMR and/or laser spectroscopy !

$\mu(^{59}\mathrm{Cu}) = +1.891(9)\ \mu_N$



^{57}Cu
test magicity of ^{56}Ni

Shell model with realistic interaction (G-matrix) and different monopole modifications



A. Lisetsky (OXBASH) ...... no quenching
—— $0.7g_s$

N. Smirnova (ANTOINE), monopole by Nowacki

Magnetic and quadrupole moments:

stringent test and input for nuclear models

COLLAPS: * β-NMR on laser-polarized ms-beams

→ g-factors and quadrupole moments of Na isotopes

M. Keim et al., Eur. Phys. J. A8, 31 (2000)
M. Keim, AIP Conf. Proc. 455 (ENAM98), 50 (1998)

→ g-factor of ^{11}Be halo nucleus W. Geithner et al., PRL 83, 3792 (1999)

→ g-factor and quadrupole moments of ^{8,9}Li and the ^{11}Li halo nucleus

D. Borremans et al., Phys. Rev. C (2005) in print
R. Neugart et al., in preparation

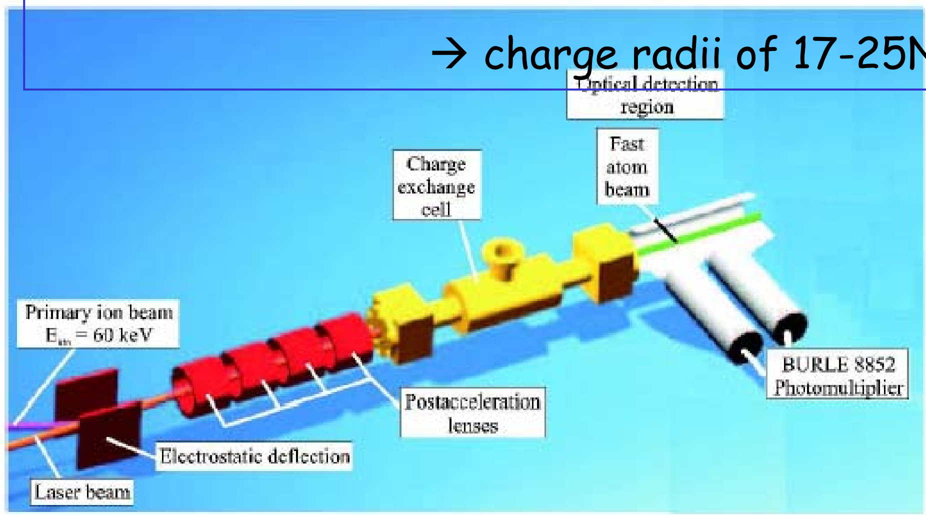
* laser spectroscopy on stable and exotic isotopes

→ g-factors of **^{17}Ne (proton halo candidate)** and of ^{23,25}Ne

from magnetic moment: **isospin symmetry with ^{17}N is preserved**
no indication of anomalous nuclear structure

W. Geithner et al., PRC 71, 064319 (2005)

→ charge radii of 17-25Ne W. Geithner, PhD thesis, Mainz and in preparation



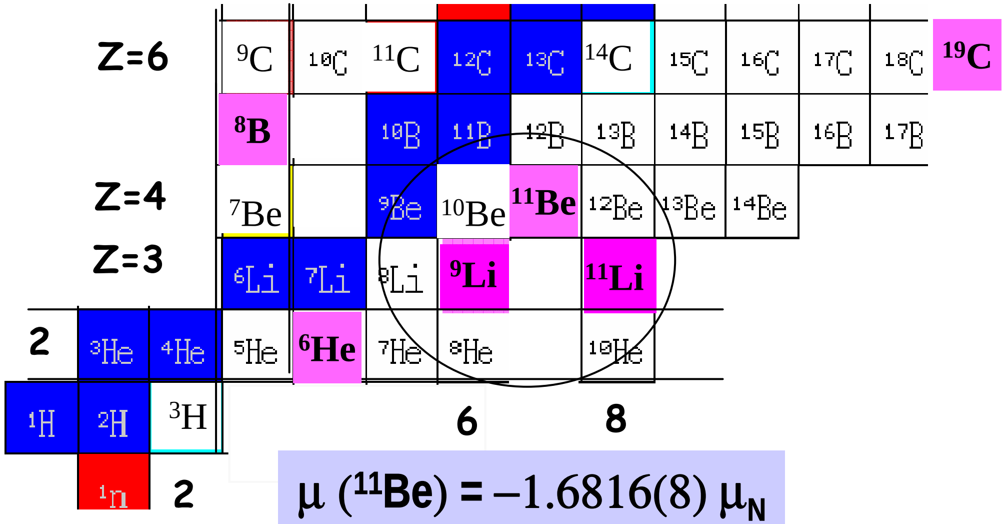
Future:
K,Ca,Sc beyond N=30
Cu-isotopes from N=28 to N=50
Zn-Ge-Ga towards and beyond N=50

Magnetic and quadrupole moments:

stringent test and input for nuclear models

COLLAPS: g-factor of the halo nucleus ^{11}Be (N=7) W. Geithner et al., PRL 83, 3792 (1999)

Q-moment of the halo nucleus ^{11}Li in preparation



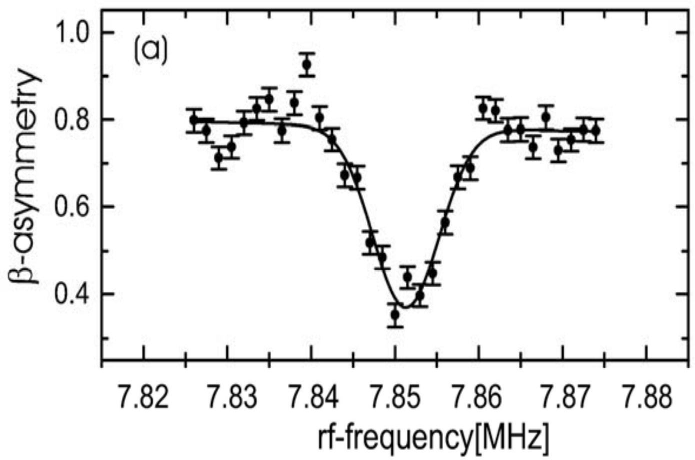
μ (^{11}Be) = $-1.6816(8)\ \mu_N$

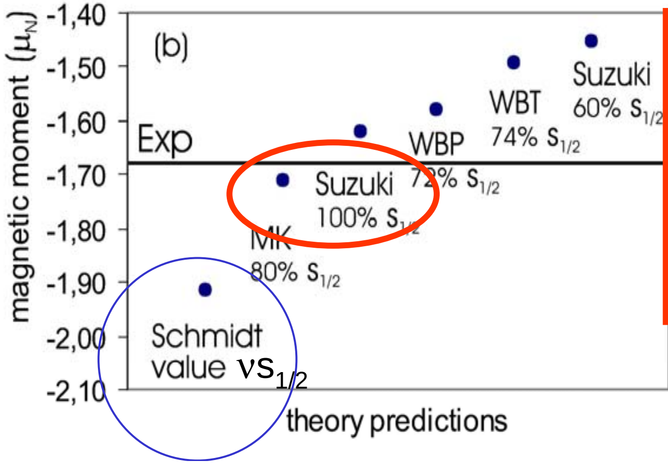
^{11}Be: $I^\pi = ½^+$ instead of $½^-$

→ neutron in intruder $2s_{1/2}$ orbit ?

admixture $2^+ \times 1d_{5/2}$?

$p_{1/2}$ neutron has $\mu_{schmidt} = +0.64\ \mu_N$



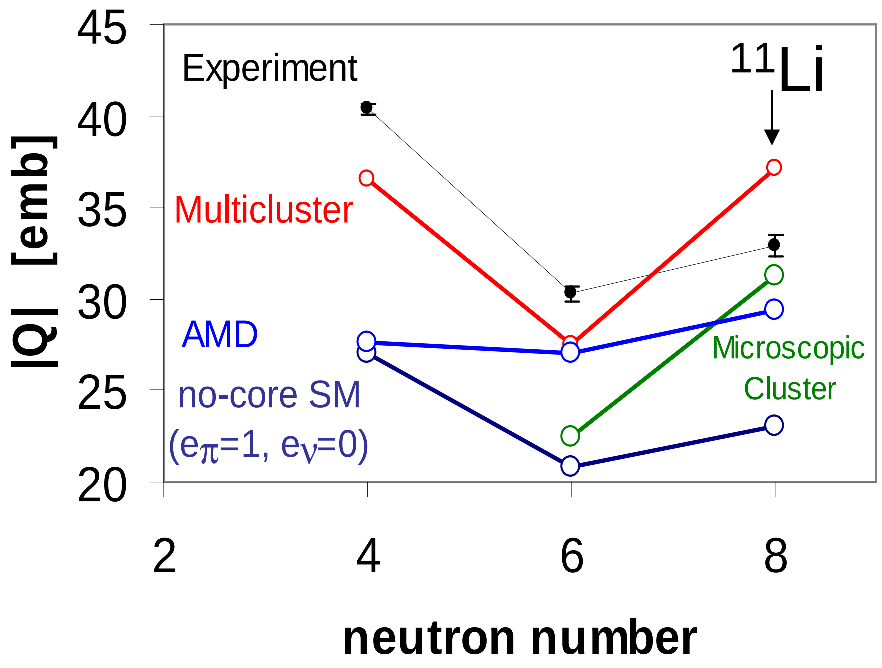


- 80% $\nu s_{1/2}$
- Suzuki adapted monopole for reduced N=8 gap → 100 % $s_{1/2}$

Magnetic and quadrupole moments:
stringent test and input for nuclear models

COLLAPS: g-factor of the halo nucleus ^{11}Be (N=7) — W. Geithner et al., PRL 83, 3792 (1999)

Q-moment of the halo nucleus ^{11}Li — in preparation



Li : Z = 3

→ $\pi p_{3/2}$ dominates ground state properties

$$^{11}Li = {}^{9}Li + 2n$$
$$= (\pi p_{3/2} + 6n) + 2n$$
$$= \pi p_{3/2} + 8n$$

→ Multicluster model (Varga et al.,)
PRC22 (2002) 041302R

→ Cluster model (Descouvement)
NPA626 (1997) 647

Overestimate the ratio Q(11Li)/Q(9Li)

→ No-core SM (Navratil et al.)
(2-body interaction: PRC57 (1998) 3119)
(3-body included: PRC68 (2003) 034305)
best agreement for trend !
if e_π=1.2e, e_ν=0.2e : good absolute agreement !

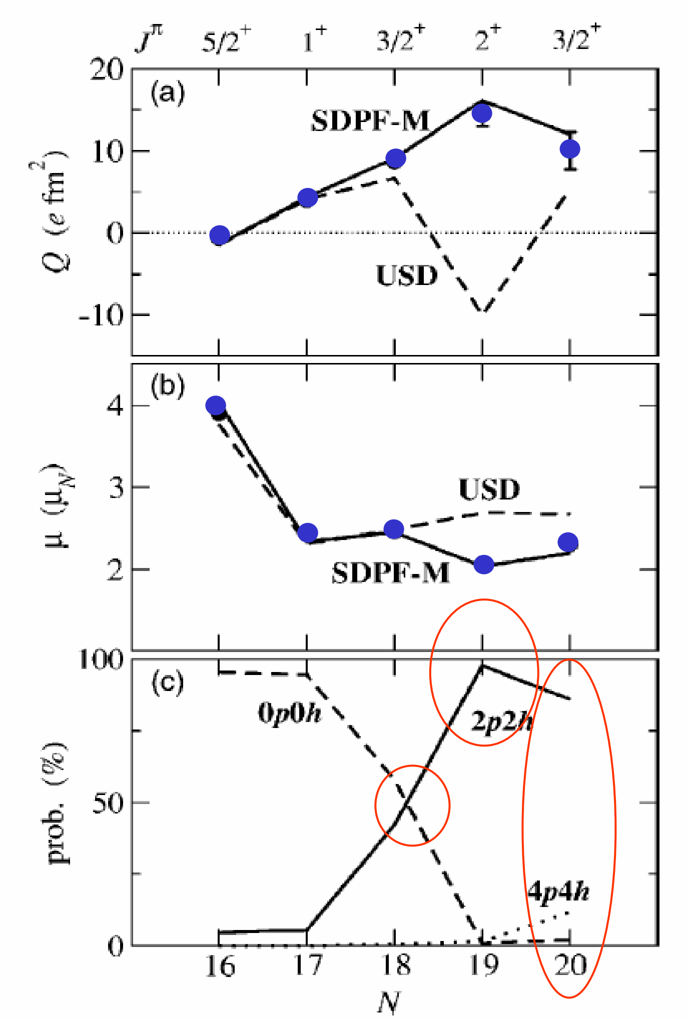
→ Antisymmetrized Molecular Dynamics
rather good agreement
better agreement for ^{7}Li
if cluster-features are included

Magnetic and quadrupole moments:
stringent test and input for nuclear models

COLLAPS: g-factors and quadrupole moments of Na isotopes

(β-NMR on laser-polarized ms-beams) M. Keim et al., Eur. Phys. J. A8, 31 (2000)

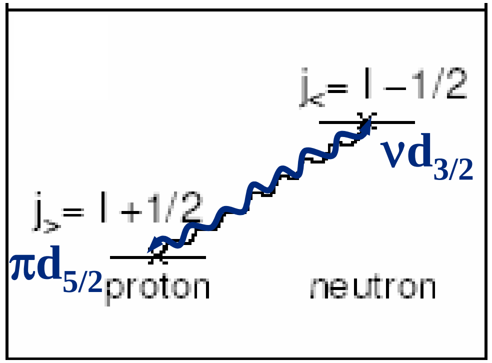
M. Keim, AIP Conf. Proc. 455 (ENAM98), 50 (1998)



N=20 : not magic for Na-isotopes (Z=11)

→ need to modify the monopole part of the residual proton-neutron interaction

T. Otsuka, PRL87 (2001) 082502



→modified monopole in the USD part of the **SDPF-M** interaction

Y. Utsuno, PRC 70, 044307(2004)

→N=18: 50% intruder admixture

→N=19: pure 2p-2h intruder

→N=20: mixed 2p-2h and 4p-4h

Strong attractive interaction between spin-orbit partners → N=20 is decreased when emptying the $\pi d_{5/2}$ orbital

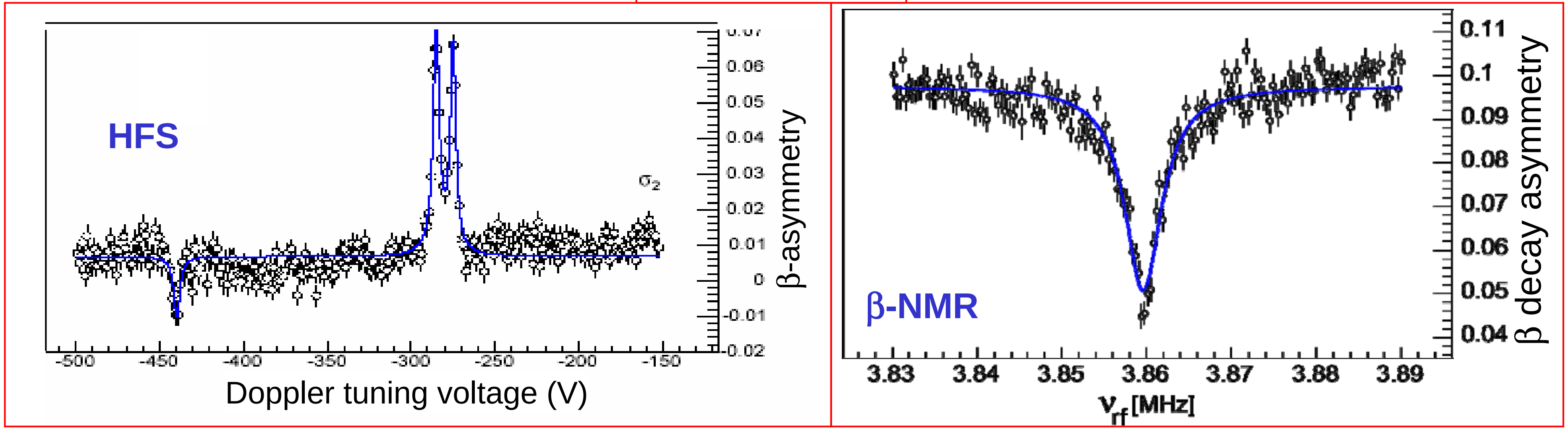
→ N=16 magic for O-isotopes (^{24}O)

Nuclear spin: the basis for a complete spectroscopy

COLLAPS: combine hyperfine structure and β-NMR to measure I and g

G. Neyens, M. Kowalska, D. Yordanov et al., Phys. Rev. Lett. 94, 022501 (2005)

^{31}Mg in MgO



31Mg (N=19) ground state spin I=1/2

g-factor is negative

g = - 1.7671(2)

→ $\mu = I.g = -0.88355(10)\ \mu_N$

Nuclear spin: the basis for a complete spectroscopy

COLLAPS: combine hyperfine structure and β-NMR to measure I and g

G. Neyens, M. Kowalska, D. Yordanov et al., Phys. Rev. Lett. 94, 022501 (2005)

IMPLICATIONS
OF A GROUND STATE $I^{\pi}=1/2^{+}$

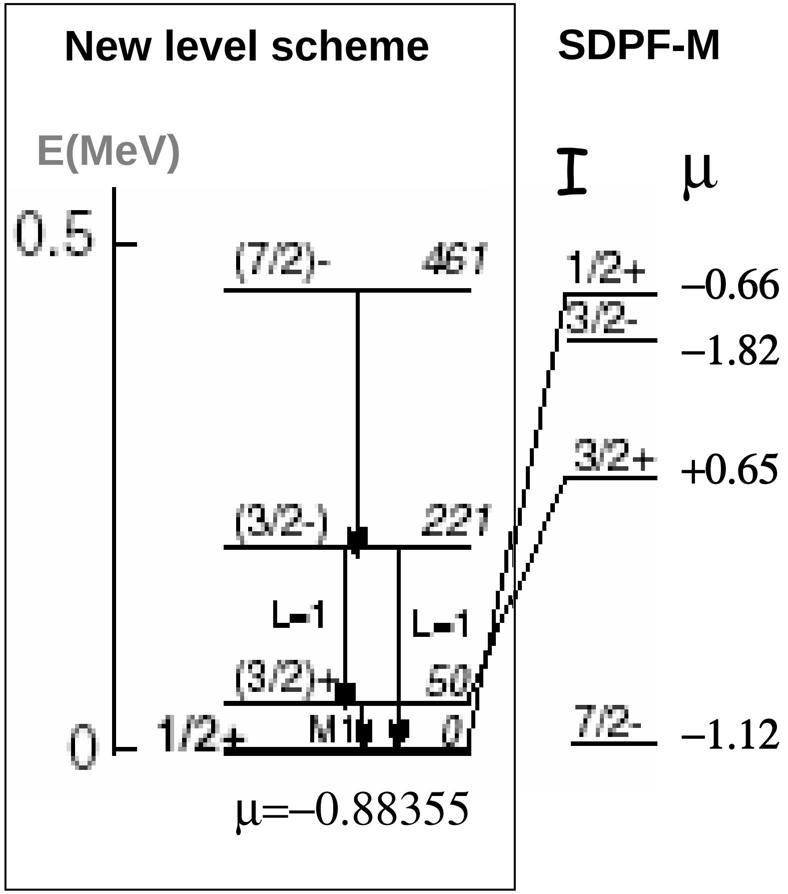
→ spin-assignments to lowest 4 states

→sd-shell model : ½+ at 2.5 MeV

→ to obtain ½+ below 500 keV requires particle-hole excitations

½+ = pure intruder state (2p-2h mainly)

→ modifications in shell model interactions needed to reproduce a ½+ ground state:
- adapt the monopole term in sd and/ or pf shells ?
- adapt the N=20 shell gap ?



Klotz et al., PRC 47, 2502 (1993)
Neyens et al., PRL 94, 022501 (2005)

The Future: needs …

Current limitations and suggested improvements:

(1) Improve sensitivity of the collinear laser techniques
to run with 10^3/s instead of 10^6/s at present (using ISCOOL)
to reach more elements (e.g. Cr – Ge region) by optimizing/investigating charge-exchange processes.

(2) Beam intensities of 10^4/s are needed in most experiments
→ an upgrade in intensity would allow reaching regions of predicted shell changes/deformation, hardly accessibly now
e.g. * the region beyond N=20 for Ne,Na,Mg
* the region beyond N=32 for K, Ca, Sc, Ti, …
* beyond ^{132}Sn (N=82 shell gap)
* neutron rich Pb-region (almost unexplored !)
→ or perform precision measurements on halo nuclei (e.g. ^{14}Be, …)

(3) Towards the proton/neutron driplines
→ contamination in laser-ionized beams needs to be suppressed !
e.g * Na isobars in ^{21}Mg, ^{22,23}Al beams
* Ga isobars in neutron rich Cu, Zn beams

Many thanks to …

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Wilfried Nörthershäuser, Rainer Neugart, Klaus Blaum, Mainz

Francois Leblanc, IPN Orsay

Spins, moments, radii:

probing changes in the nuclear shell structure

... nuclear moments → magnetic moment μ

→ probes the configuration (mixing)

→ very sensitive to changes in the structure due to monopole migration

→ allows in some cases firm spin-assignments

→ the quadrupole moment **Q**

→ probes collective properties of nuclei (deformation, core polarization)

→ the nuclear spin **I**

→ basis for further spin-determinations !

... charge radii → measure $\delta\langle r^2\rangle$ → probes changes in charge deformation

→ demonstrates the halo-nature of dripline nuclei