Study of neutron-rich ^{52,53}K isotopes by the measurement of spins, moments and charge radii

CERN-INTC-2016-008 / INTC-P-458

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General physics motivations in Ca region ($Z = 20$)

- **3N forces:**
  - -- an important role to describe shell structure /spectra of n-riched Ca isotopes.
  - -- needed to explain N=28 shell closure using microscopic interaction.

  ----- J.D. Holt et al., J. Phys. G: Nucl. Part. Phys. 39, 085111 (2012).

★ **The calcium and neighboring isotopic chains lie at the frontier of theoretical calculations with 3N forces.**

----- K. Hebeler, J.D. Holt et al., Annu. Rev. Nucl. Part. Sci. 65, 457 (2015).

- **Ab-initio calculation:**
  - -- binding energies and low-lying excitation spectra of Ca isotopes.
  - -- predicted the (E2+) of ^{54}Ca before experimental data available

  ----- G. Hagen et al., Phys. Rev. Lett. 109, 032502 (2012)

★ **The region around ^{54}Ca provides an excellent experimental venue to confront predictions using ab-initio.**

----- The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE (United States)

- **New magic numbers $N = 32$, $N = 34$**
  - -- suggested in Ca chain and its neighbors.

  ----- F. Wienholtz et al., Nature 498, 346 (2013).
  ----- D. Steppenbeck et al., Nature 502, 207 (2013).

Previous laser spectroscopy studies

Provide nuclear ground state properties (**Nuclear spins, moments, and charge radii**)

			20							28				32		34
***Z* = 21**	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
***Z* = 20**	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
***Z* = 19**	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53

IS-484 **Ground-state properties of K-isotopes from laser and β-NMR spectroscopy**

Results: PRL 110, 172503 (2013);
PRC 90, 034321 (2014) : Shell evolution in K isotopes
PRL 113, 052502 (2014); p-n Pairing Correlations in the Self-Conjugate Nucleus ^{38}K
PLB 731, 97 (2014); Evolution of nuclear size above *N*=28

IS-529 **Moments, Spins and Charge Radii Beyond ^{48}Ca**

Results: PRC 91, 041304 (2015): First test of microscopic interaction NN+3N from chiral EFT
Nature Physics (2016): First test of ab-initio CC calculation including 3N forces

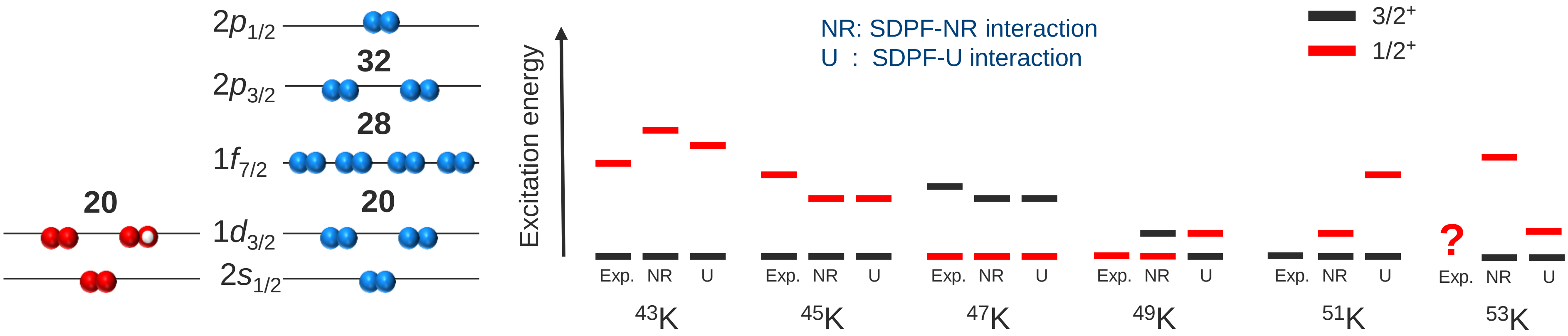
IS-529: On-going (^{53,54}**Ca**), ROC project at COLLAPS

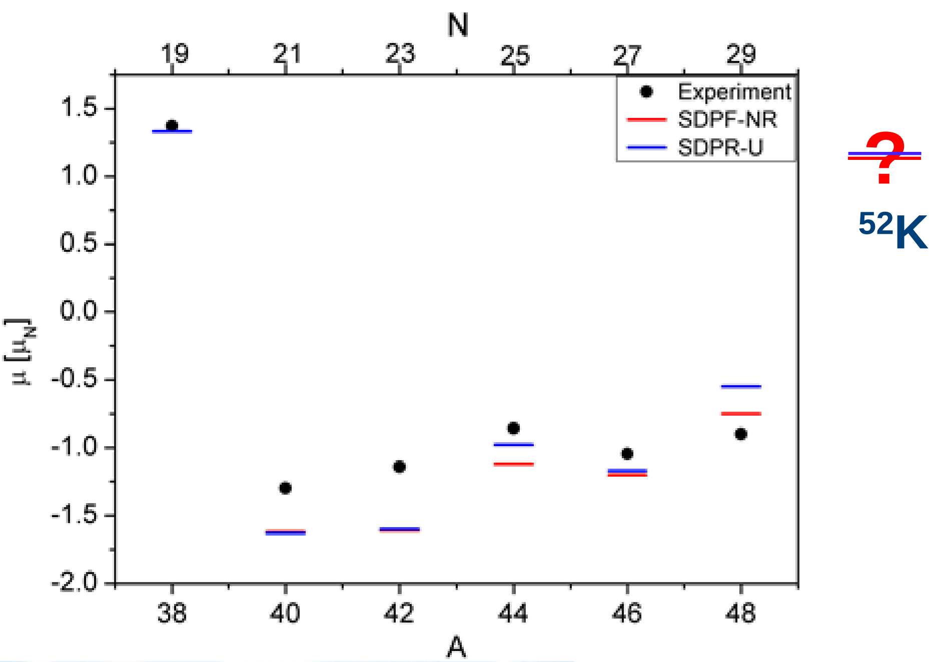
INTC-P-450: Planning ($^{47-51}$**Sc**), at COLLAPS

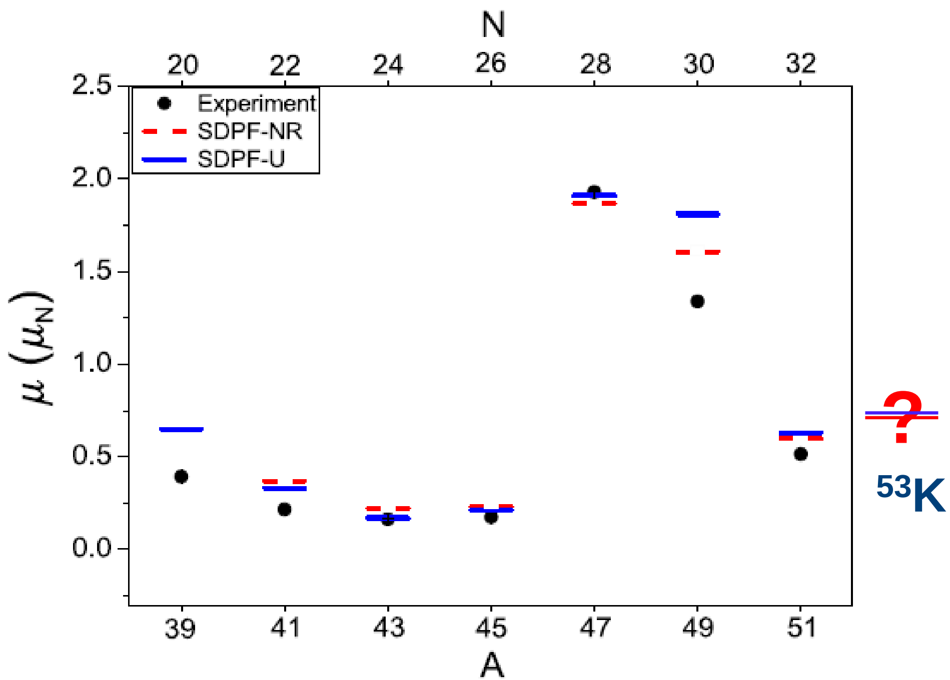
INTC-P-451: Planning ($^{51-54}$**Sc**), at CRIS

INTC-P-458: This proposal (^{52,53}**K**), at CRIS

What do we know about K? (Nuclear spins and magnetic moments)







What happened to the proton sd shell as neutron $\nu p_{1/2}$ orbit is filled ??

--**Need the spins and magnetic moments of ^{52,53}K**

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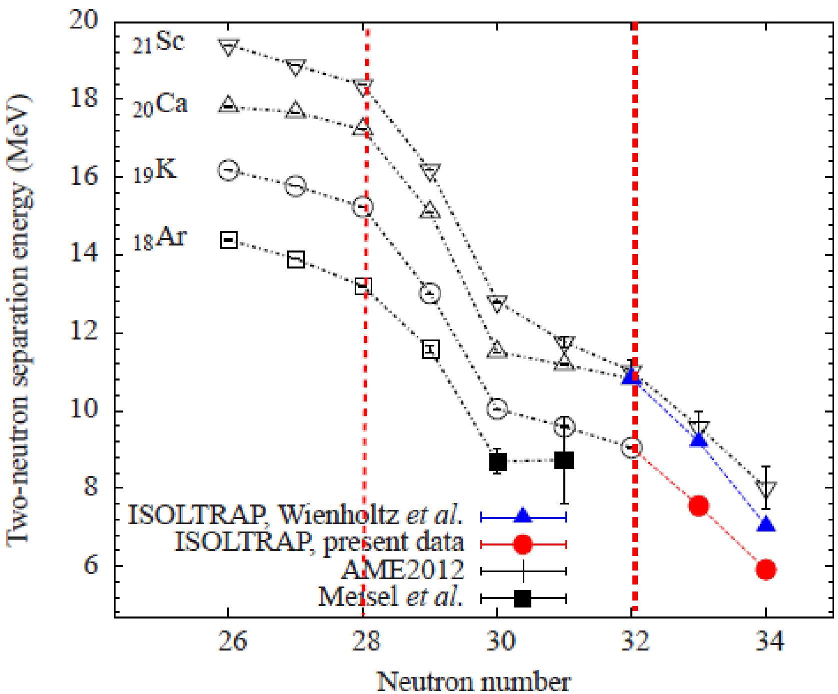
J. Papuga et al., PRC 90 034321 (2014), PRL 110, 172503 (2013)

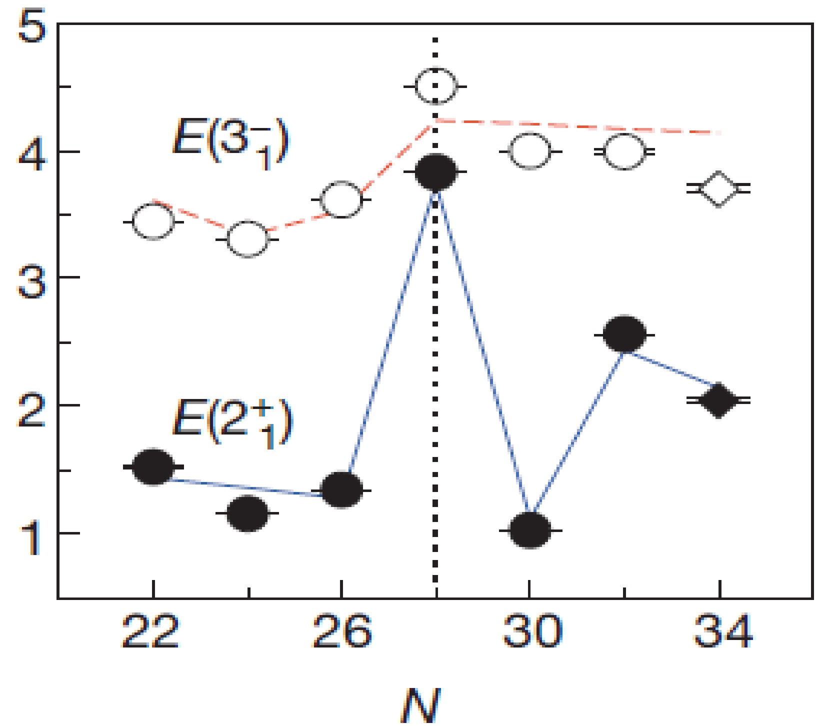
“New ‘magic’ numbers (N = 32, N = 34)”!!

K, Ca (Z = 19,21): S_{2n}



Wienholtz et al., Nature 498, 346 (2013).
Rosenbusch et al., PRL 114.202501 (2013).

Ca (Z = 20) : E(2^+)



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

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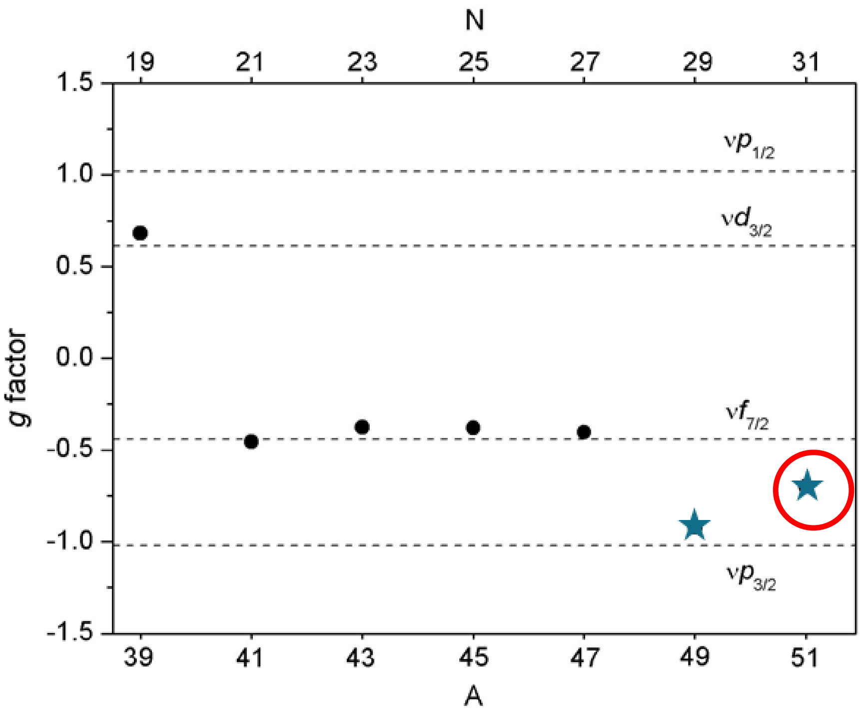
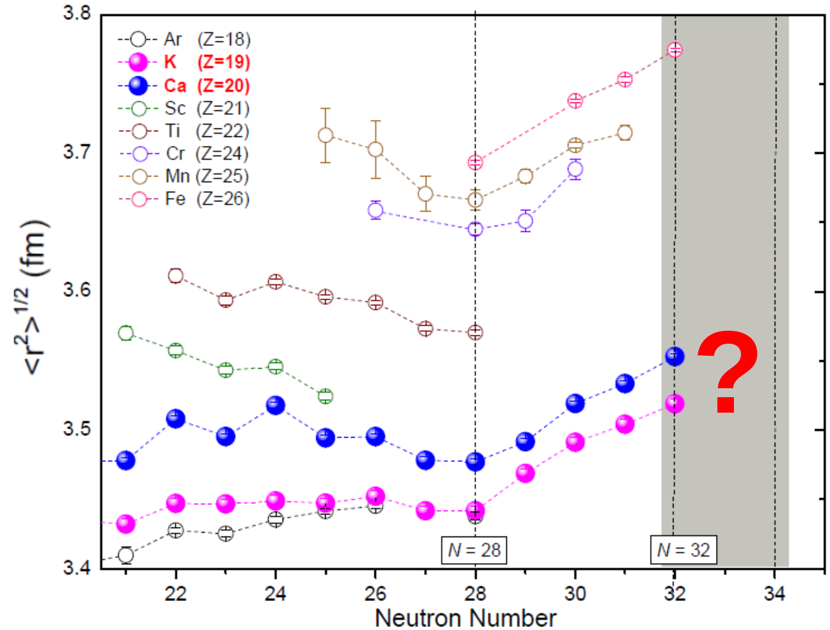
"New 'magic' numbers (N = 32, N = 34)" ??



Garcia Ruiz *et al*, PRC **91** 041304 (2015)



Garcia Ruiz *et al*, Nature Physics 2016,
Kreim *et al*, PLB **731** 97 (2014)

- ^{51}Ca isotope
  ---has a single hole in the "double magic" ^{52}Ca.
- g-factor measurement from Collaps
  --- with some mixing configurations due to neutron excitations across N = 32

- Similar increase as Fe isotopic chain
  --no shell closure is expected

Need charge radii measurements across N = 32 in Ca region

--charge radii of ^{52}K (N = 33): the key information to test the N = 32

-- charge radii of ^{53}K (N = 34) : provide information on the N = 34

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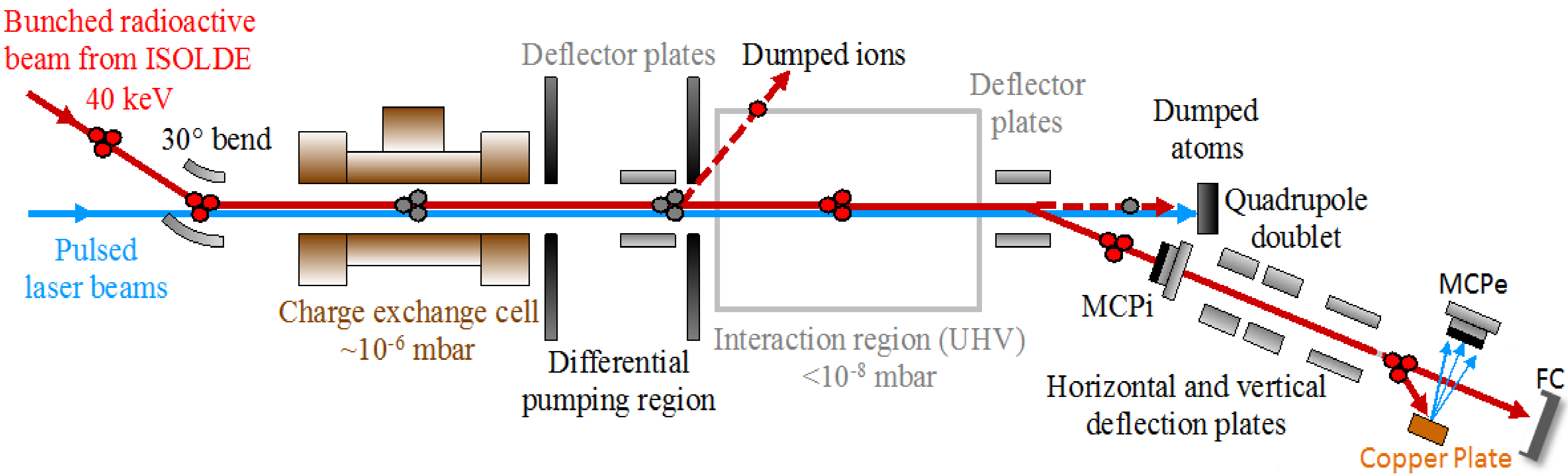
Experimental method: CRIS

Collinear Resonance Ionization Spectroscopy



- Using current standard CRIS setup.
- An additional MCPi is installed recently, providing a better detection efficiency.
- Using atomic transition to get hyperfine structure (spins, moments, charge radii).
- Off-line tests have achieved > 80 % neutralization for K ions using the current CEC.

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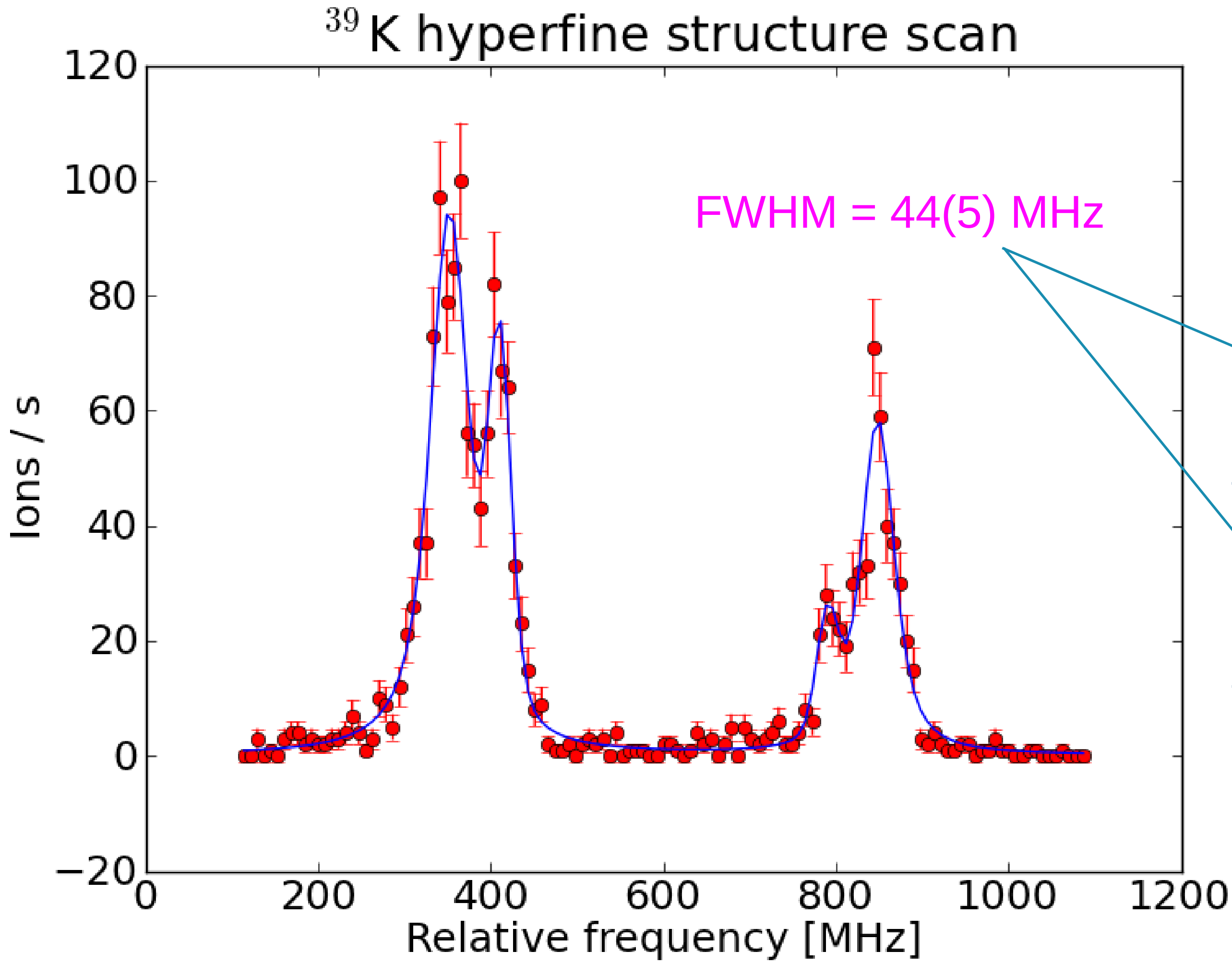
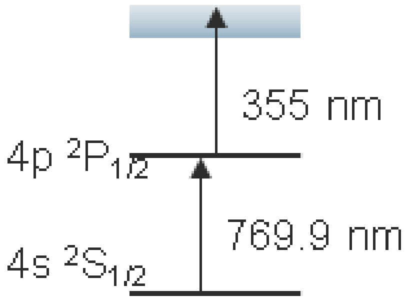
Offline test for ^{39}K



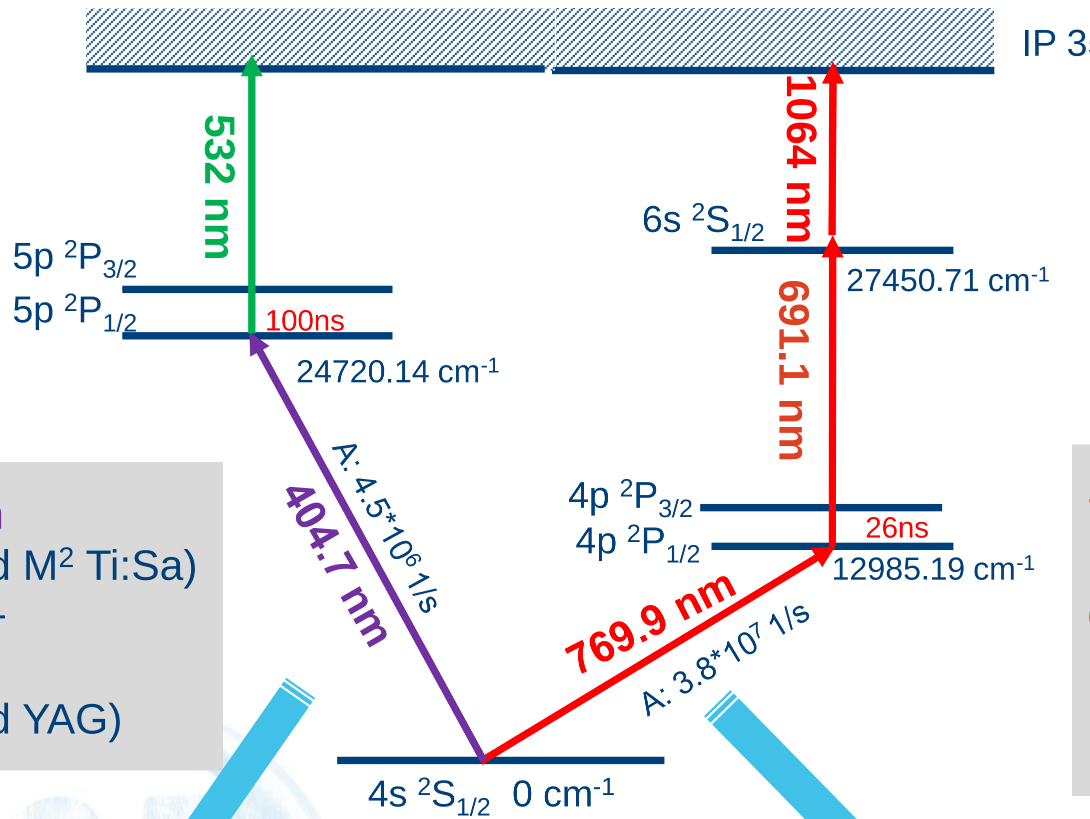


30MHz is estimated from the Doppler spread of 5kV for the offline ion source

6MHz is from the natural linewidth of 769.9 nm transition.

To avoid possible background associated with non-resonant ionization from 355nm laser

Resonance ionization of scheme for K



404.7nm
(Doubled M² Ti:Sa)
+
532 nm
(Doubled YAG)

769.9nm (M² Ti:Sa)
+
691.1nm (Pulsed Dye)
+
1064 nm (YAG)

--Similar transition as Fr atom
--Expect same ionization efficiency

--Used in K run at COLLAPS
--Used in the K offline test at CRIS

769.9nm/404nm transition for obtaining the hyperfine structure of ^{52,53}K isotopes

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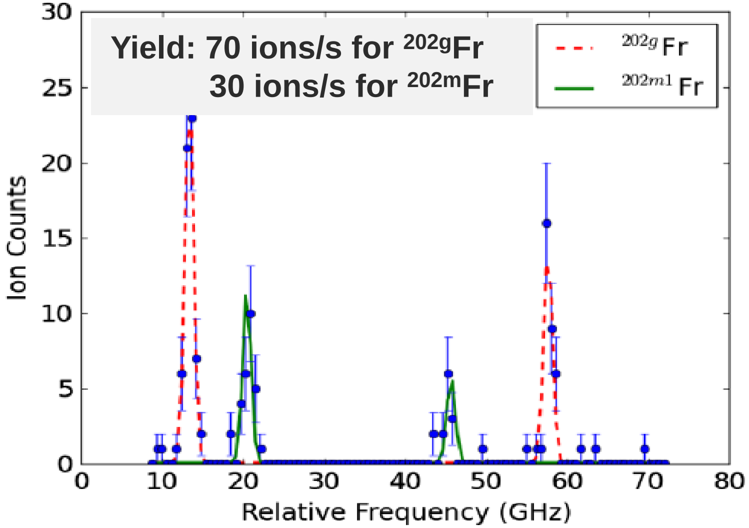
BEAM TIME request

Spectra taken in 2 h (2012)



$$\varepsilon_{Total} = \varepsilon_{Transmission}\ \varepsilon_{Neutralization}\ \varepsilon_{Laser\ ionization}\ \varepsilon_{Detection}$$

- **Transmission:** standard CRIS beamline as for Fr
- **Neutralization:** >80% (K) better than for Fr 50-70 %
- **Detection:** A better detection efficiency with 2nd MCP
- **Laser ionization:** a comparable ionization efficiency with Fr

Isotopes	half life	yield (ions/s)	Target/ion source	shifts
^{51}K	365 ms	4500	UC_x /WSI	1 (^{47,48,51}K)
^{52}K	105 ms	560	UC_x /WSI	2
^{53}K	30 ms	~ 50	UC_x /WSI	6
References				2
Total				11
Stable beam				2

-2 shifts of stable beam for optimizing the experimental set-up and laser scheme
-11 shifts of radioactive K isotopes to measure the hyperfine structure
-- **Spins, magnetic moments and isotopes shift of K isotopes**

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Thanks for your attention!

CRIS

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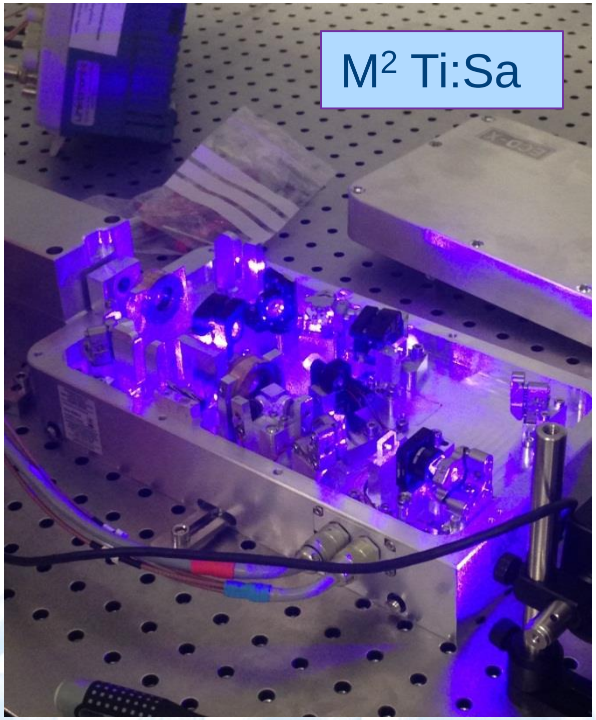
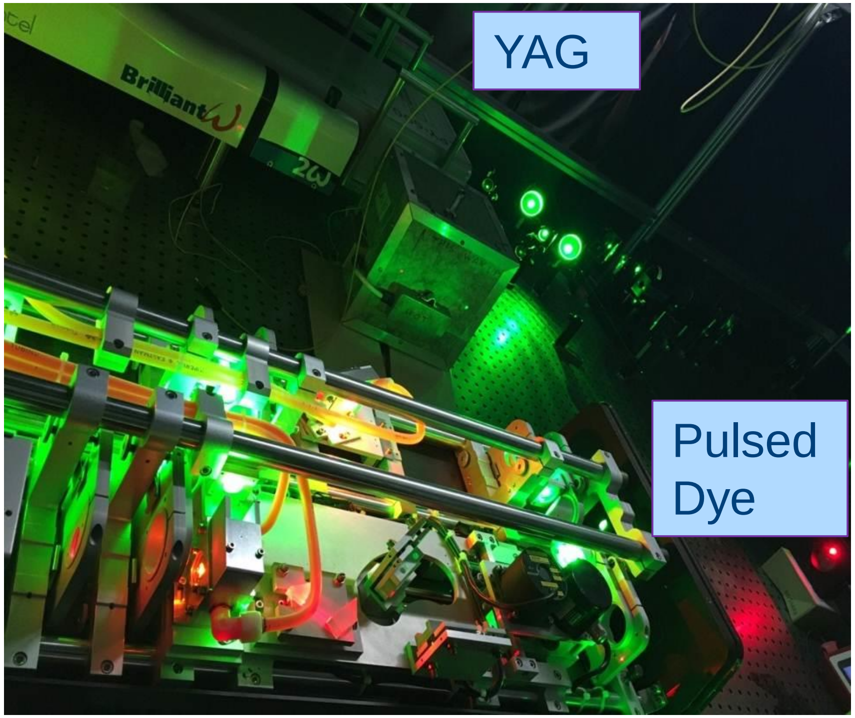
-- 769.9nm **(M² Ti:Sa)** + 696.1nm (Pulsed Dye) +1064 nm(YAG, 200Hz)

M² Ti:Sa : >4W





Doubled M² Ti:Sa: >1W

-- 404.7nm **(Doubled M² Ti:Sa)** + 532 nm (Doubled YAG, 100 Hz)

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An injection seeded laser in CRIS can provide more powerful narrow band laser

How to get the fundamental properties (spins, moments, charge radii) ?

Hyperfine structure (HFS)-> link between atomic parameters and nucleus parameters

$$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}$$

Atomic parameters

- Magnetic dipole HF parameter

$$A = \frac{\mu_I B_J}{IJ}$$

- Electric quadrupole HF parameter

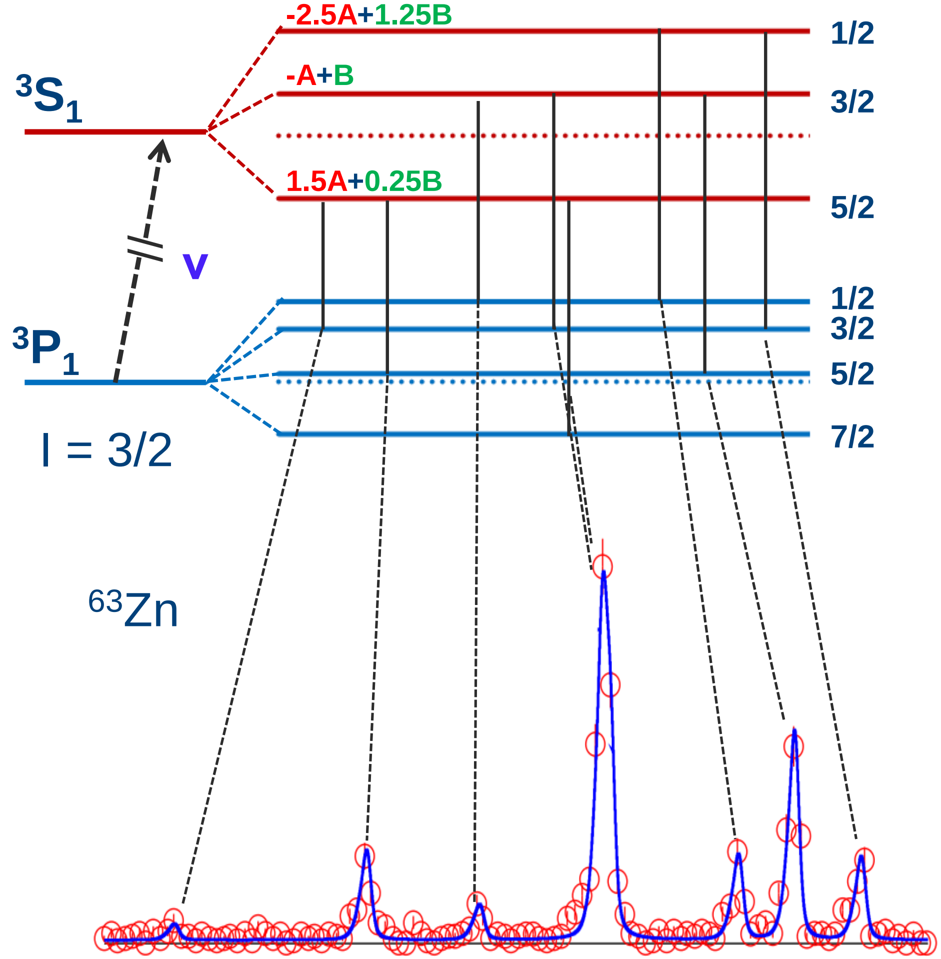
$$B = eQV_{zz}$$

- Centroid ν_0
  Isotopes shift

HFS

Nucleus parameters

-the nuclear spin **I**
-the magnetic dipole moment **μ**
-the electric quadrupole moment **Q**
-nuclear charge radius $\langle r^2 \rangle$



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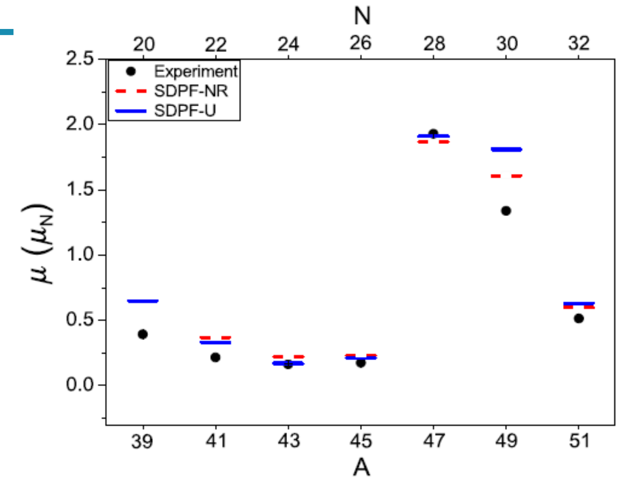
A compelling test for theory model

- **Shell model (SM)**

  -- Phenomenological SM calculation agree well with experimental results up to *N* = 32 (SDPF-U. SDPF-NR)

  PRL 110, 172503 (2013); PRC 90, 034321 (2014)



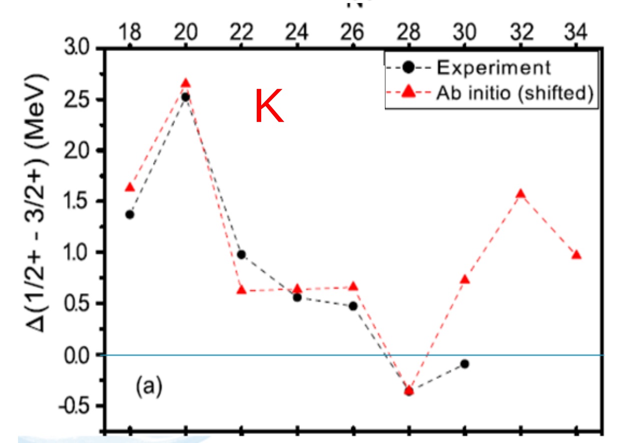
- **Ab initio (including 3N)**

  Self-Consistent Green's Functions (SCGF)

-- Predicating the general trend of proton sd orbit evolution

-- Planning to calculate the moment in Ca mass region

PRC 90, 034321 (2014)



Magnetic moments of ^{52,53}K, with one proton-hole added to the Ca core

-- be a compelling test of the validity of SM interaction beyond *N* = 32

-- be an important test for further developments of microscopic interactions

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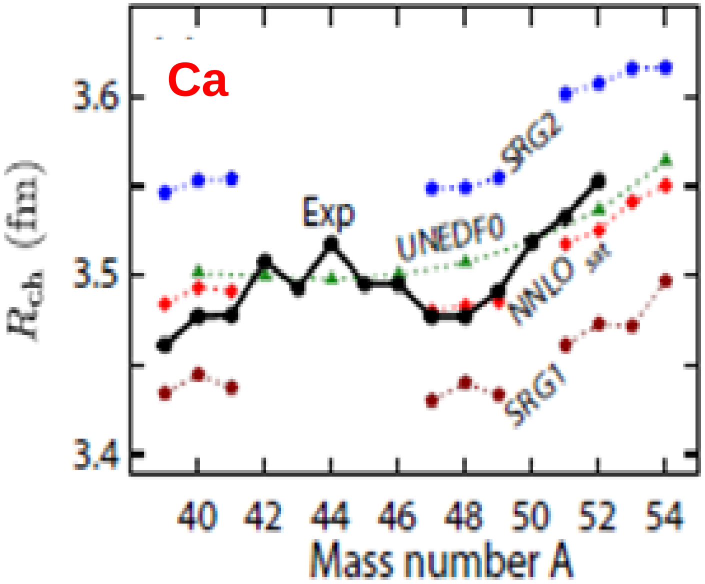
A compelling test for theory model

Charge radii of ^{52,53}K

"The accurate reproduction of nuclear radii of medium-mass nuclei is a long-standing challenge in nuclear theory" ***----A. Ekstrom et al PRC 91 (2015)***



Very recently

•Ab-initio calculations using Coupled cluster method has been applied to describe charge radii of medium mass nuclei (Ca).

G. Hagen *et al*, Nature Physics 2015

•It is ideally suited for nuclei with at most one or two nucleons outside a closed (sub-) shell.

Garcia Ruiz *et al*, Nature Physics 2016

Charge radii of ^{52,53}K isotope

--suitable and thus a good test for the calcualtions

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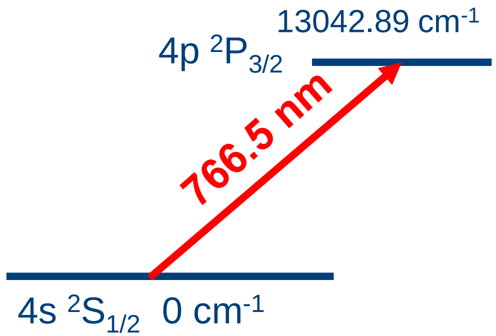
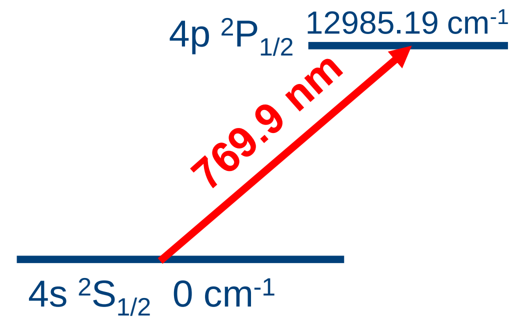
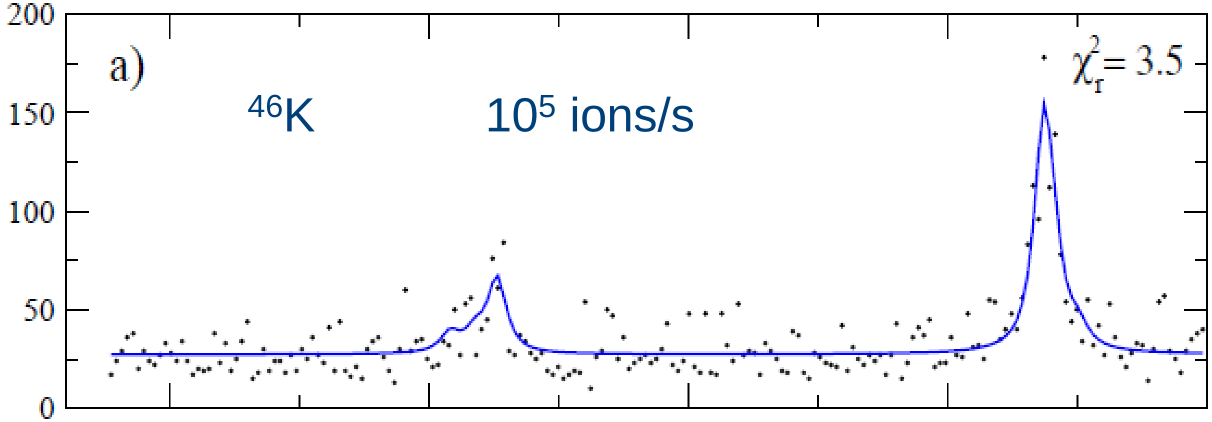
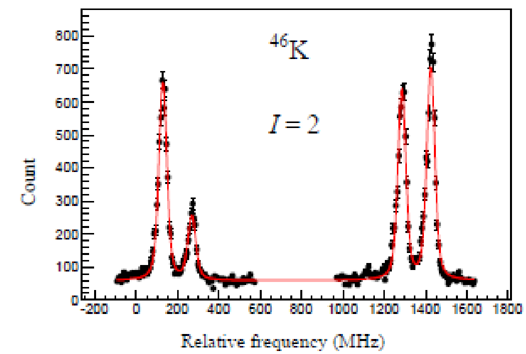
(4s-4p transition) 42(6) MHz.

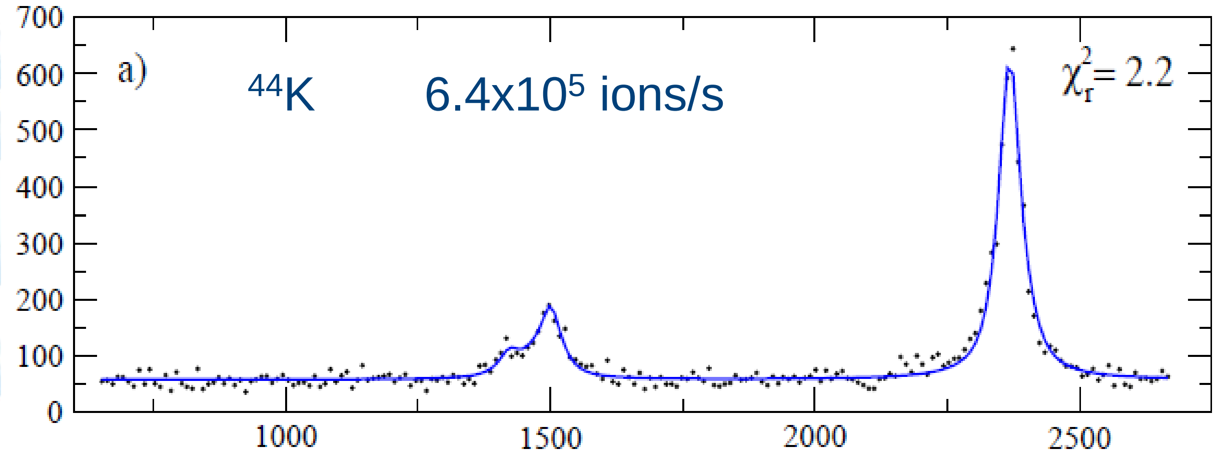
A	B $P_{3/2}$ (MHz)	Q(b)
44	$+25 \pm 1.5$	$+0.52 \pm 0.3$
46	$+27.4 \pm 5.4$	$+0.57 \pm 0.11$

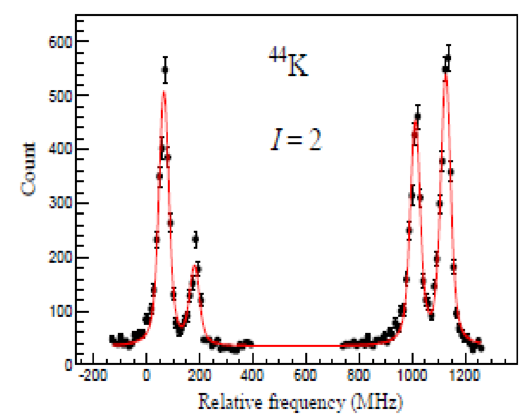












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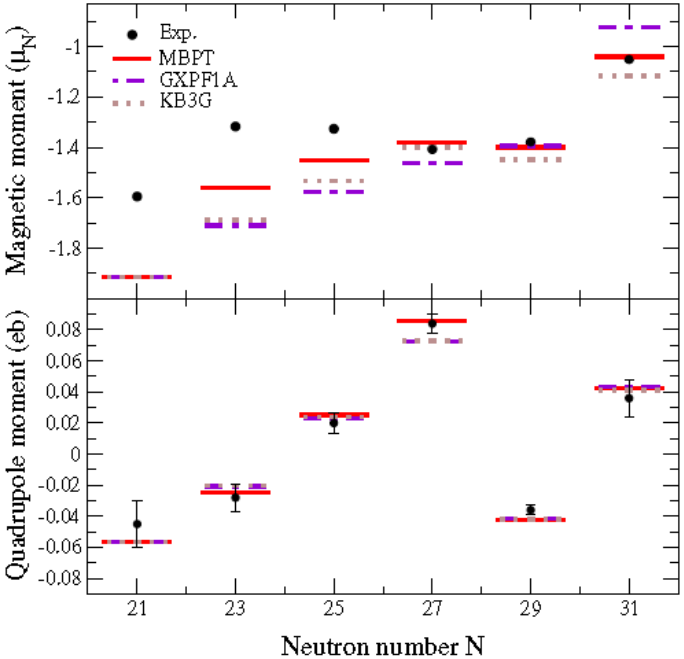


Annu. Rev. Nucl. Part. Sci. 2015. 65

S. Pastore et al
PRC 87, 035503 (2013)

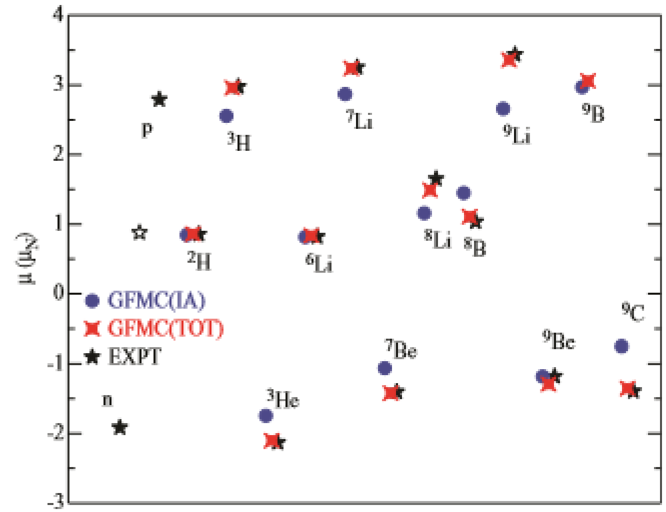
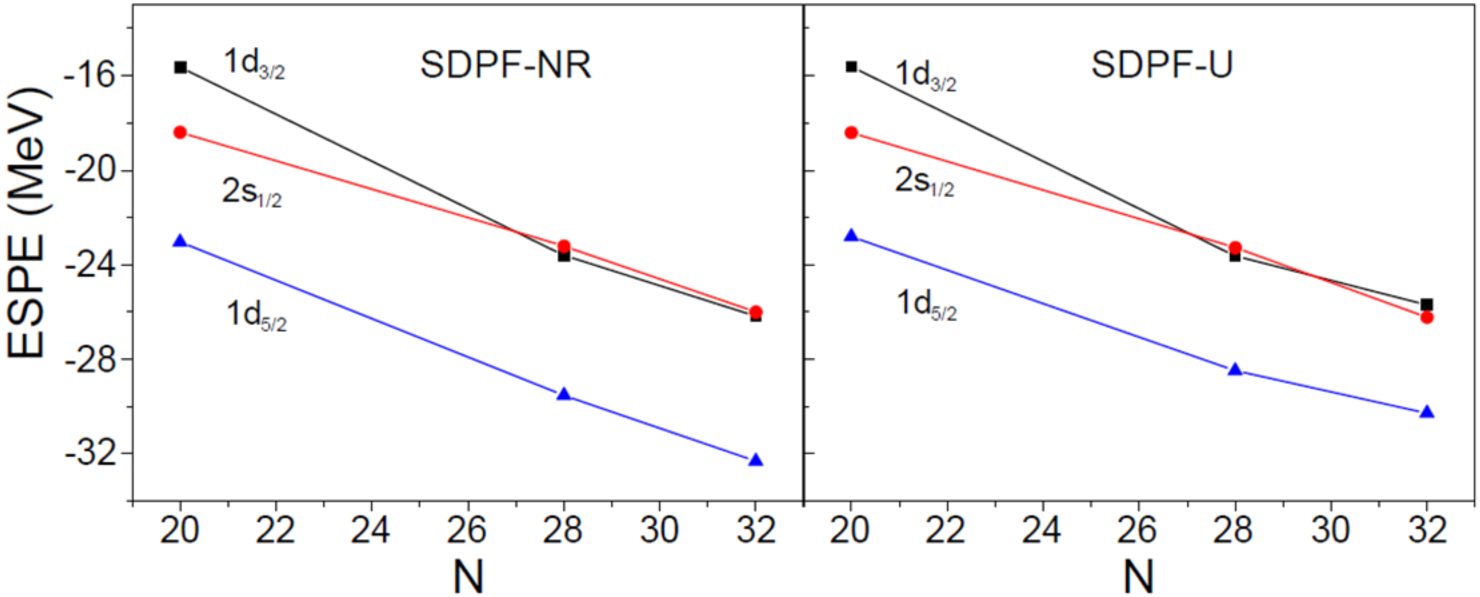
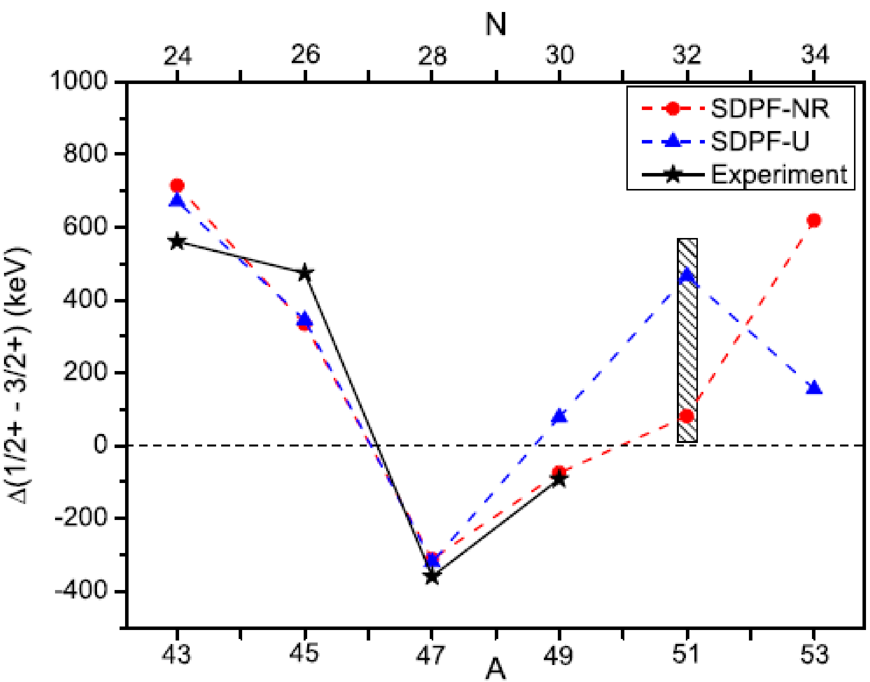


FIG. 4. (Color online) Magnetic moments in nuclear magnetons for $A \leqslant 9$ nuclei. Black stars indicate the experimental values [35–37], while blue dots (red diamonds) represent GFMC calculations which include the IA one-body EM current (total χEFT current up to N3LO). Predictions are for nuclei with $A > 3$.

This inconsistency and the sensitivities to different interactions (compared to the smaller spread for the quadrupole moments) point to the need for systematic calculations of magnetic momentoperators in the valence space. Necessary improvements are the inclusion of electromagnetic two-body currents (or meson-exchange currents), which are derived in chiral EFT consistently with nuclear forces, as well as controlled calculations of effective operators. Results with chiral two-body currents in light nuclei demonstrate that they provide signiant contributions to magnetic moments while first applications to medium-mass nuclei have focused on Gamow-Teller transitions

Proton sd shell evolution in K isotopic chain





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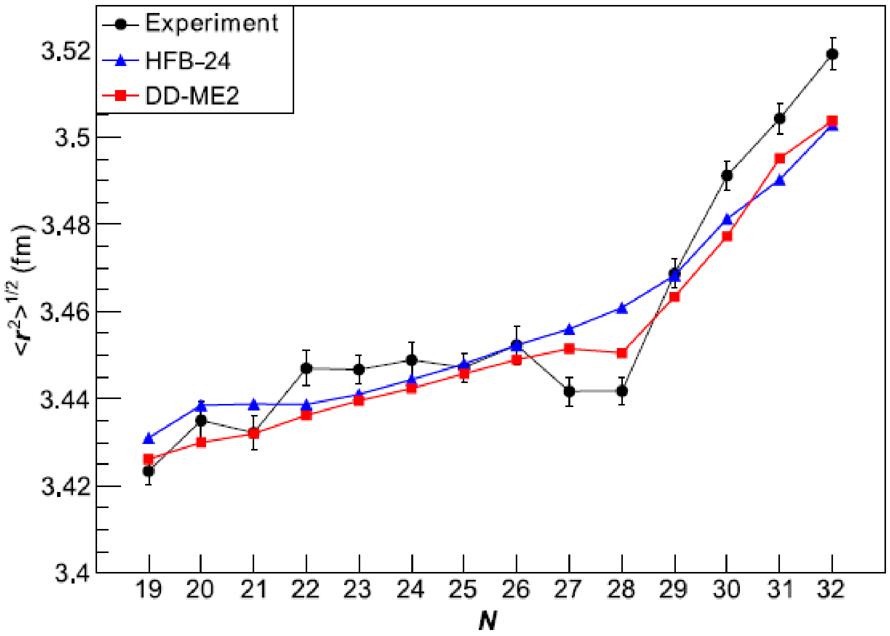
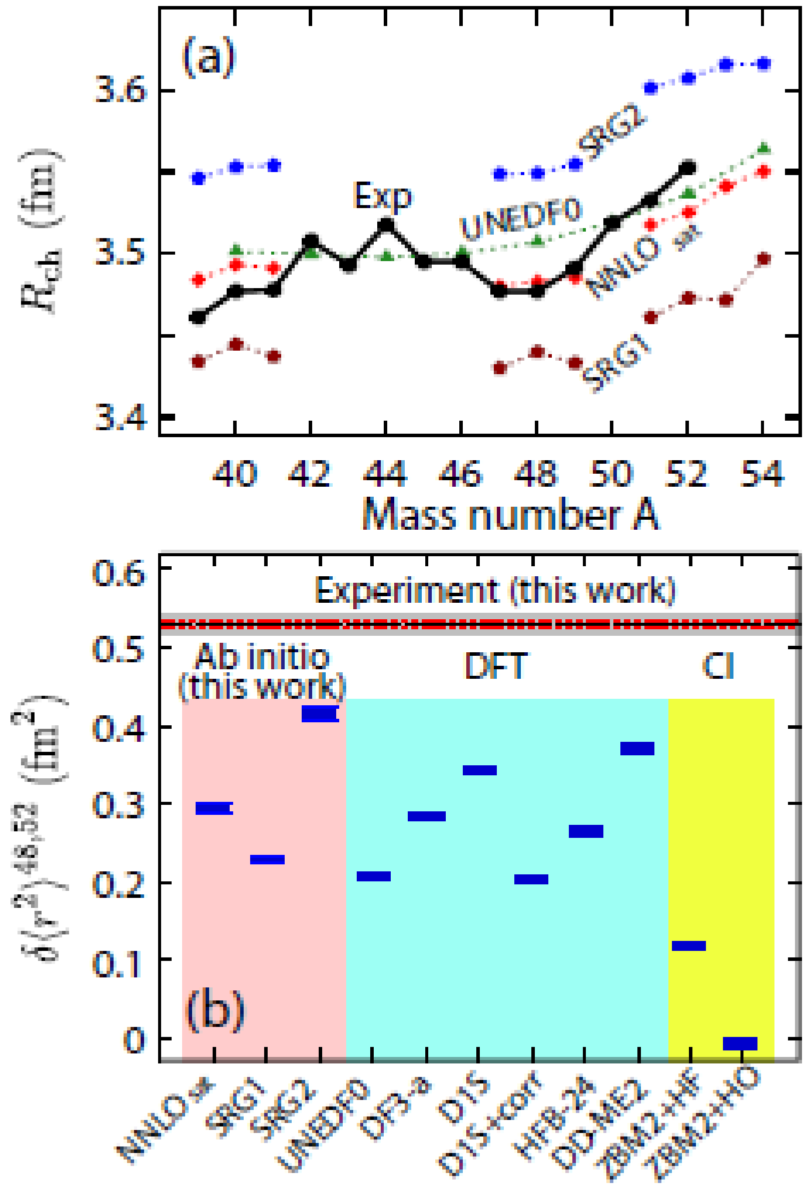
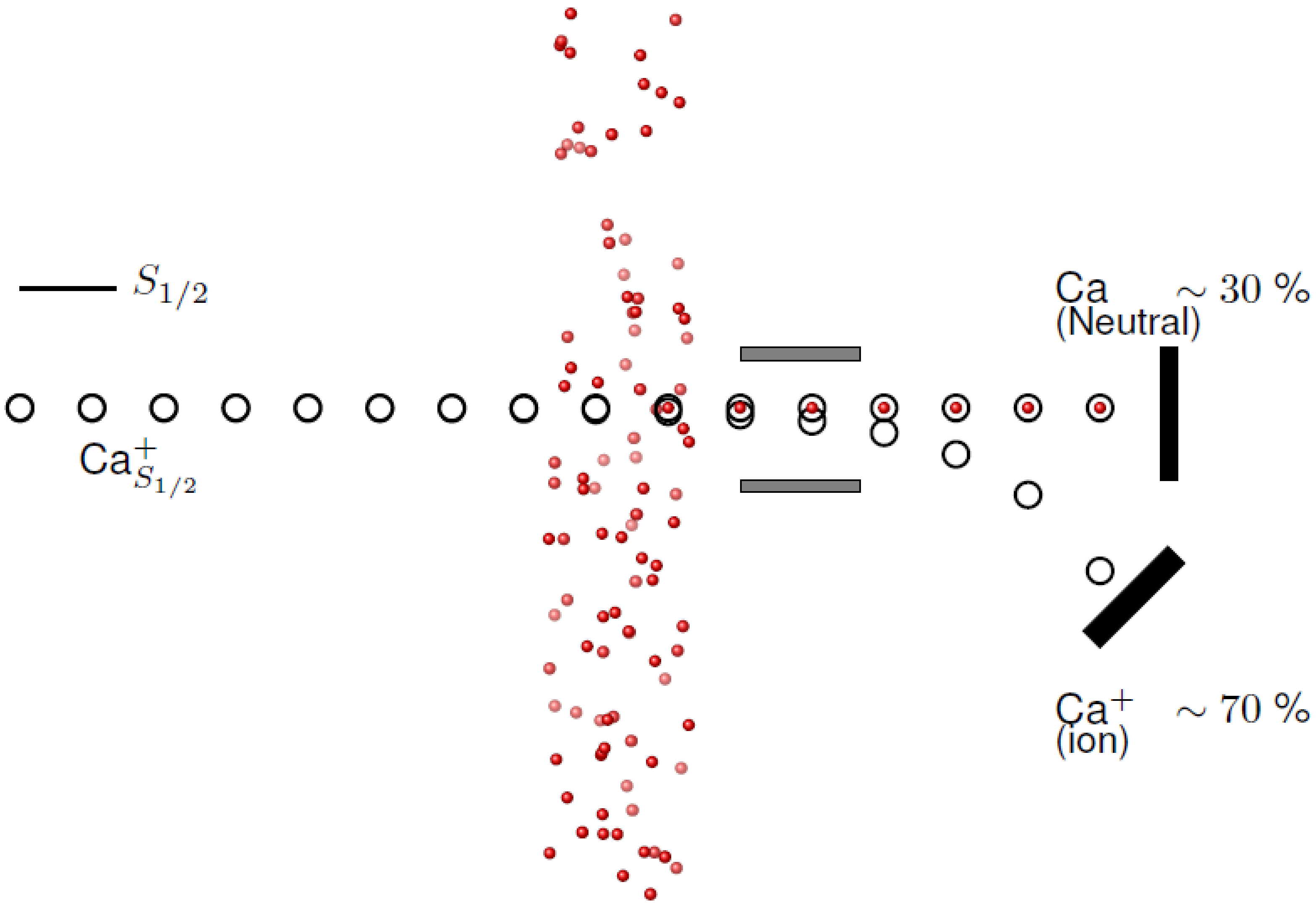
Charge radii in Ca region and theoretical calculation





Charge exchange cell (CEC)



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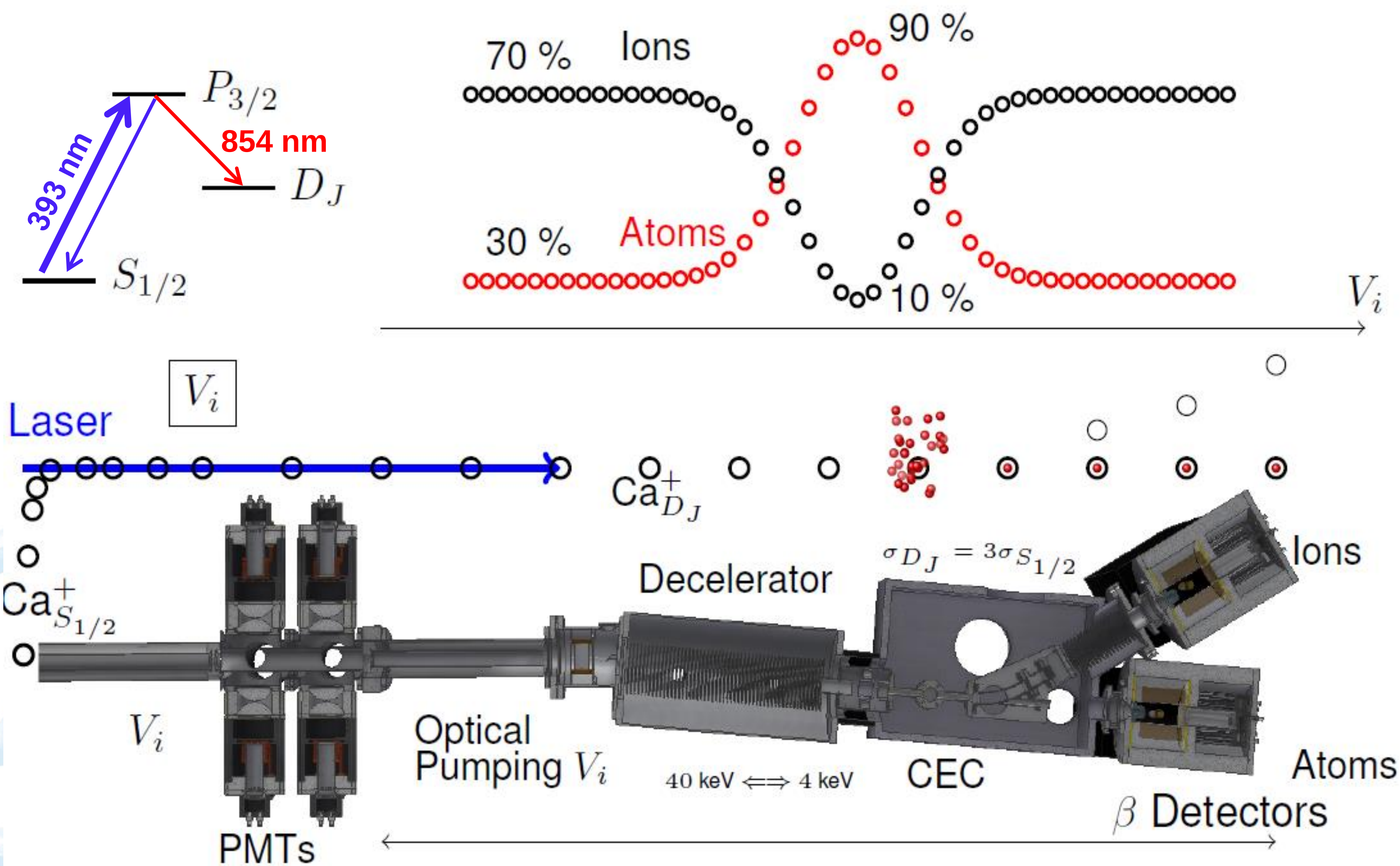

R. Garcia Ruiz, Ph. D thesis, KU Leuven (2015)

Results of K from COLLAPS

39K, Aup 9.02(17)MHz
(4s-5p transition)

$\Delta \nu$ = 454.2(8) MHz

TABLE I. Magnetic hyperfine parameters for neutral potassium from this work and comparison with literature values [32–34].

Isotope	I^π	$A(^2S_{1/2})$ (MHz)	$A(^2P_{1/2})$ (MHz)	$A_{\text{lit}}(^2S_{1/2})$ (MHz)	$A_{\text{lit}}(^2P_{1/2})$ (MHz)
^{38}K	3^+	+404.3 (3)	+48.9 (2)	+404.369 (3)	–
^{38m}K	0^+	0	0	–	–
^{39}K	$3/2^+$	+231.0 (3)	+27.8 (2)	+231.0 (3)	+27.5(4)
^{42}K	2^-	−503.7 (3)	−61.2 (2)	−503.550779 (5)	−60.6(16)
^{44}K	2^-	−378.9 (4)	−45.8 (2)	−378.1 (11)	−44.9(11)
^{46}K	2^-	−462.8 (3)	−55.9 (2)	−465.1 (12)	−55.7(13)
^{47}K	$1/2^+$	+3413.2 (3)[a]	+411.8 (2)	+3420.2 (29)	+411.9(50)
^{48}K	1^-	−795.9 (3)	−96.3 (3)	–	–
^{49}K	$1/2^+$	+2368.2 (14)	+285.6 (7)	–	–
^{50}K	0^-	0	0	–	–
^{51}K	$3/2^+$	+302.5 (13)	+36.6 (9)	–	–

[a]After reanalysis, the uncertainty on this value was increased from 0.2 to 0.3 MHz.

Isotope	I^π	μ_{exp}	$\mu_{\text{SDPF-NR}}$	$\pi 1d_{3/2}^{-1}$ (%)	$\mu_{\text{SDPF-U}}$	$\pi 1d_{3/2}^{-1}$ (%)	μ_{lit}	Reference
^{39}K	$3/2^+$	+0.3917 (5) [12]	+0.65	100%	+0.65	100%	+0.3914662 (3)	[35]
^{41}K	$3/2^+$	–	+0.37	95%	+0.33	95%	+0.2148701 (2)	[35]
^{43}K	$3/2^+$	–	+0.22	92%	+0.17	92%	+0.1633 (8)[a]	[32]
^{45}K	$3/2^+$	–	+0.23	88%	+0.21	90%	+0.1734 (8)[a]	[32]
^{47}K	$1/2^+$	+1.9292 (2) [58]	+1.87	13%	+1.91	13%	+1.933(9)[a]	[32]
^{49}K	$1/2^+$	+1.3386 (8) [40]	+1.61	21%	+1.81	15%	–	–
^{51}K	$3/2^+$	+0.5129 (22) [15]	+0.60	90%	+0.65	93%	–	–
^{53}K	(3/2+)		+0.69		+0.70			

TABLE VII. Experimental magnetic moments (in units of μ_N) for even-A K isotopes compared to shell-model predictions using two effective interactions: SDPF-NR and SDPF-U. The error in the square brackets is due to the hyperfine structure anomaly, which amounts to 0.5%.

Isotope	I^π	μ_{exp}	$\mu_{\text{SDPF-NR}}$	$\mu_{\text{SDPF-U}}$	μ_{lit}	Reference
^{38}K	3^+	+1.3711 (10) [69]	+1.33	+1.33	+1.371 (6)[a]	[32]
^{40}K	4^-	–	−1.63	−1.63	−1.2964 (4)[b]	[39]
^{42}K	2^-	−1.1388 (7) [57]	−1.58	−1.56	−1.14087 (20)[b]	[34]
^{44}K	2^-	−0.8567 (9) [43]	−1.05	−0.90	−0.856 (4)[a]	[32]
^{46}K	2^-	−1.0464 (7) [52]	−1.21	−1.18	−1.051 (6)[a]	[32]
^{48}K	1^-	−0.8997 (3) [45]	−0.77	−0.55	–	–
^{52}K	(2-)		+1.22	+1.22		

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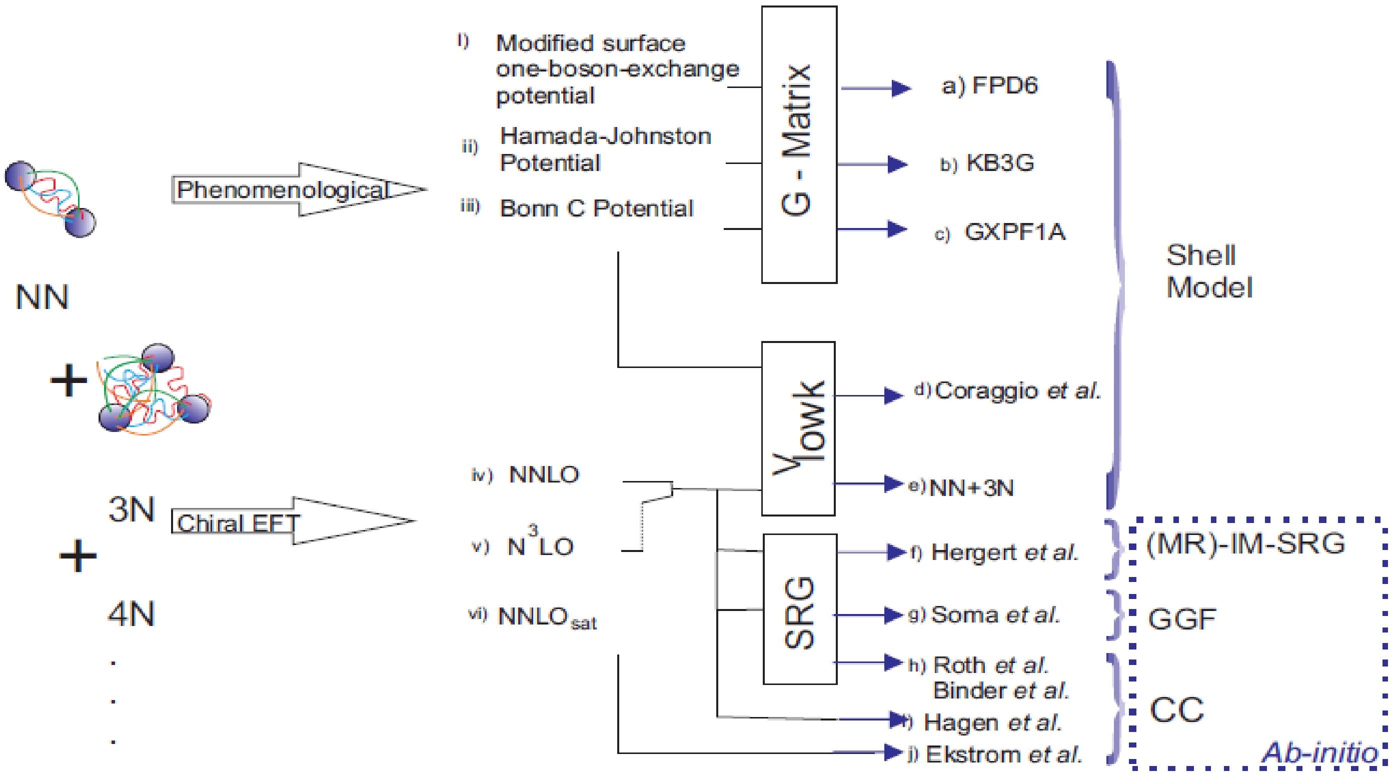

Figure 3.5: Nucleon-nucleon potential and effective interactions developed for Ca isotopes. The "bare" nucleon-nucleon potential is transformed into an "effective" interaction by using the most common methods: G-matrix, SRG, and V_{lowk}. The "effective" Hamiltonian is then used to calculate nuclear structure observables with the shell-model approach or/and *ab-initio* calculations. See text form more details. References: i) [119], ii) [114], iii) [117], iv) [98, 28], v) [120, 121], vi) [122], a) [119] b)[115], c)[116], d) [123, 124], e) [29, 33], f) [125], g) [126], h) [127, 31], i) [30], j) [122].

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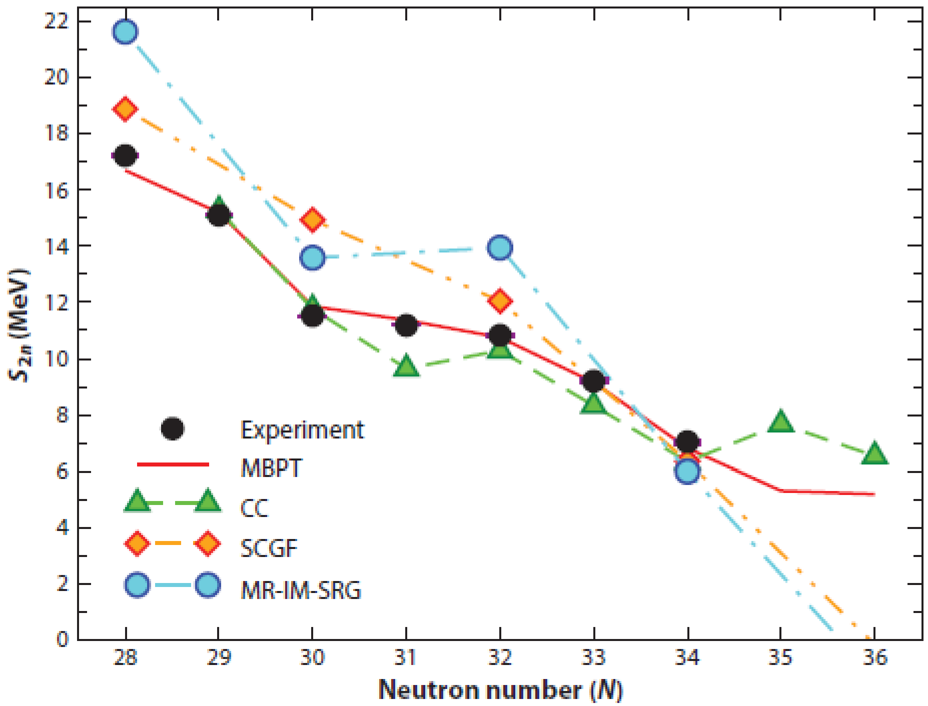

Figure 7

Two-neutron separation energy S_{2n} in neutron-rich calcium isotopes as a function of neutron number N. The experimental energies (45, 69, 75) are compared with MBPT predictions (69, 75) based on low-momentum NN+3N forces and CC theory with phenomenological $3N_{eff}$ (78). Also shown are SCGF (80) and MR-IM-SRG (81) results based on an SRG-evolved NN+3N-full Hamiltonian. Abbreviations: CC, coupled cluster; MBPT, many-body perturbation theory; MR-IM-SRG, multireference in-medium similarity renormalization group; SCGF, self-consistent Green's functions.

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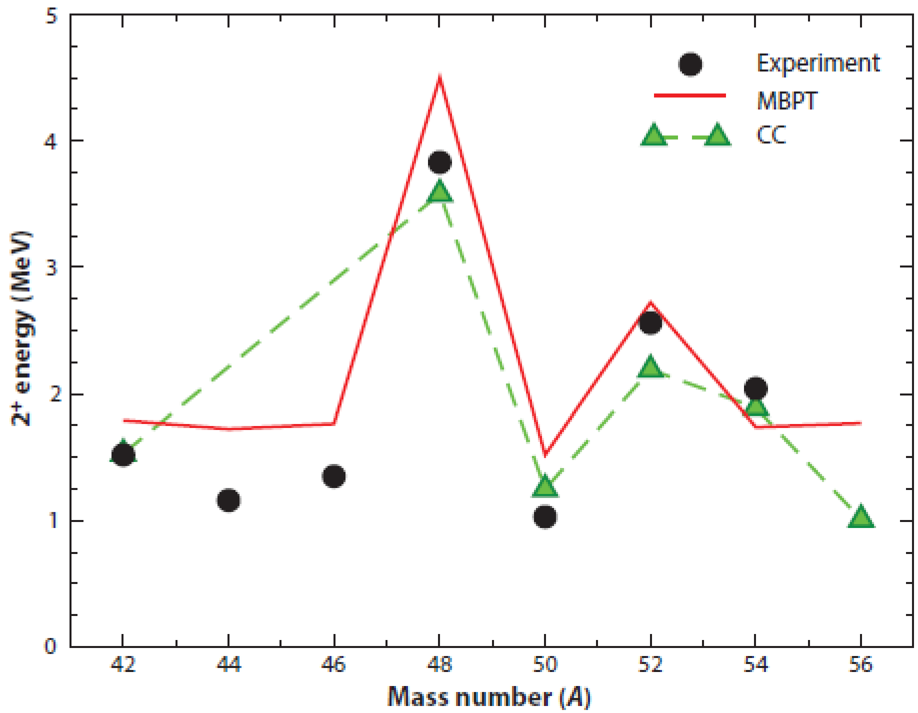
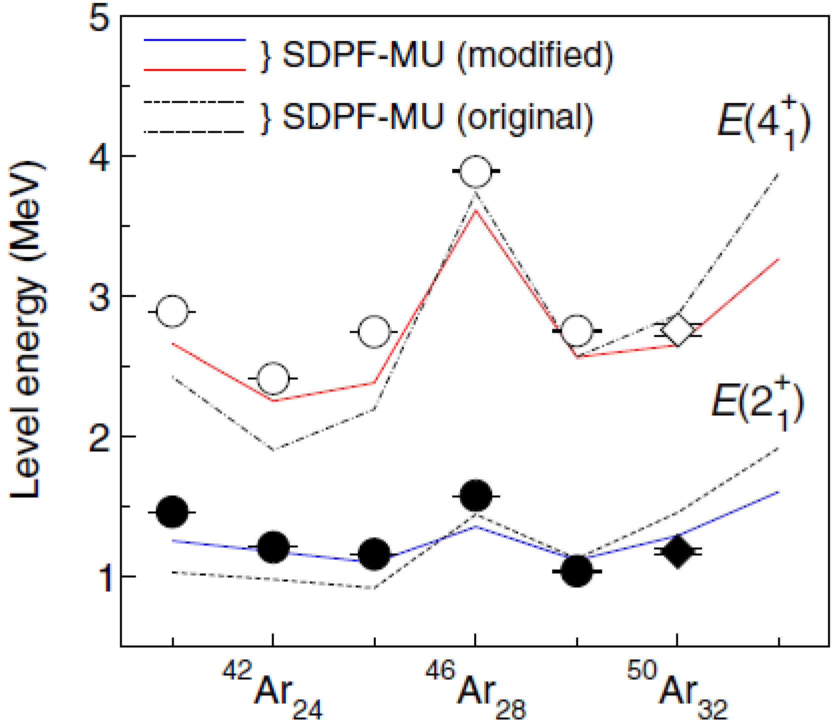


Figure 8

Excitation energy of the first 2^+ state in the even calcium isotopes as a function of mass number A. The MBPT (77) and CC results (78) corresponding to the S_{2n} calculations of Figure 7 are compared with experimental values from Reference 70 and **http://www.nndc.bnl.gov/ensdf/**. Abbreviations: CC, coupled cluster; MBPT, many-body perturbation theory.

N =32 shell closure at Ar



As mentioned above, the rise in $E(2_1^+)$ is naively suggestive of a sizable $N = 32$ subshell gap along the Ar isotopic chain. Indeed, the modified SDPF-MU interaction indicates that the magnitude of the $N = 32$ subshell closure in ^{50}Ar (~2.3 MeV) is comparable to the $N = 32$ gaps in ^{52}Ca and ^{54}Ti (~2.4 and 2.5 MeV, respectively), where the experimental evidence for the $N = 32$ closure is compelling [15–18,21]. Here, the magnitude of the

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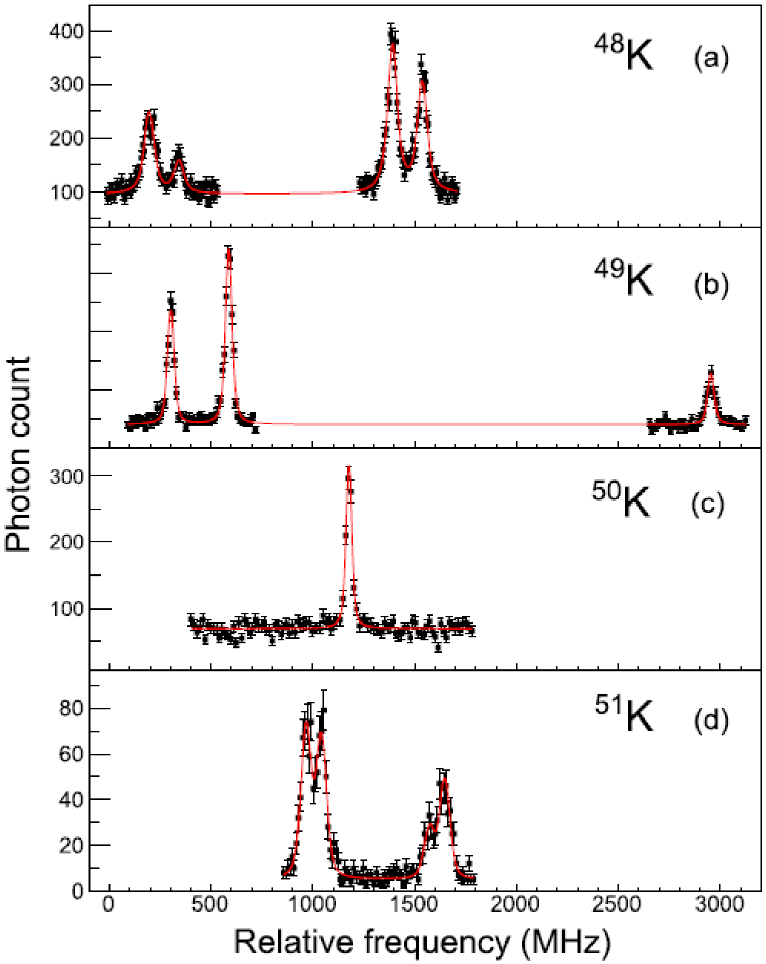
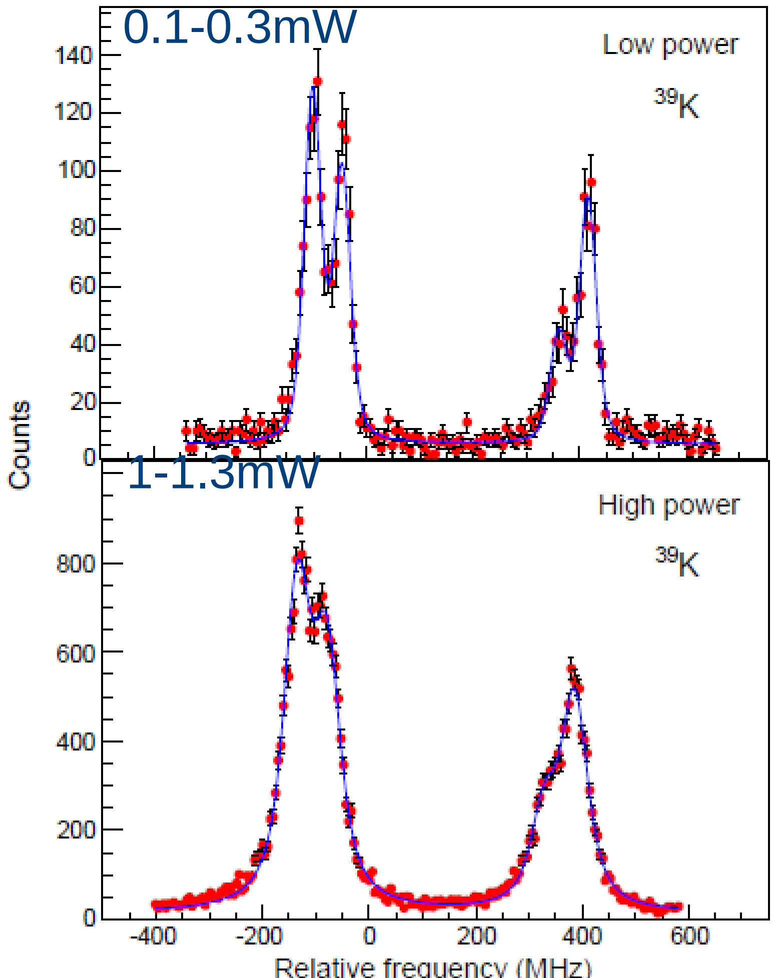
Spectra of K from COLLAPS



L = 11.5 (22)MHz and *G* = 33.1 (20) MHz



L = 44.7 (18)MHz and *G* = 30.3 (25)MHz

J. Papuga, Ph. D thesis, KU Leuven (2015)

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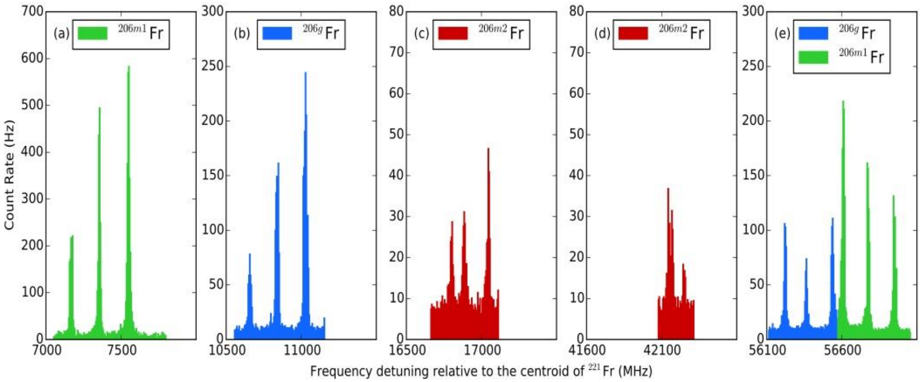
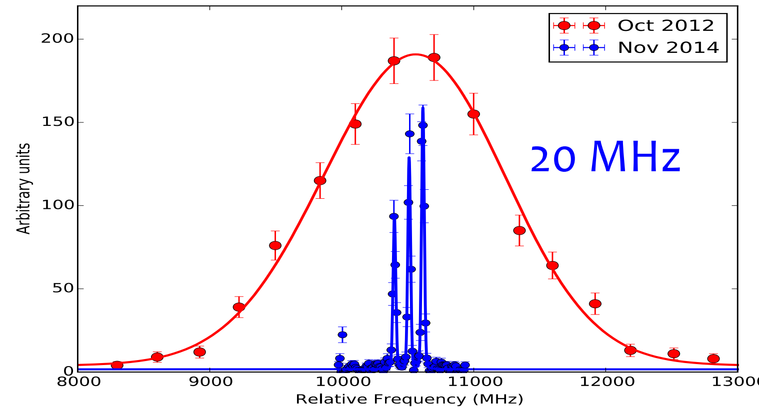
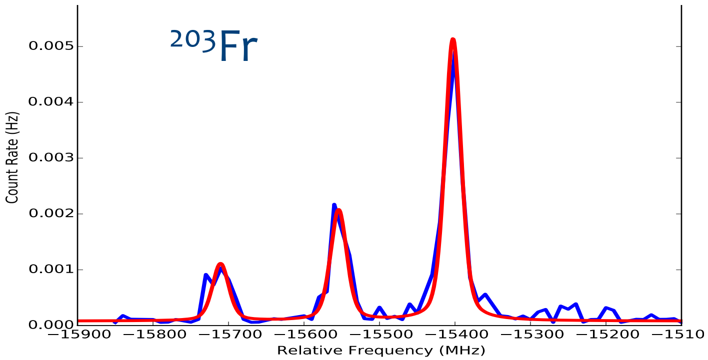
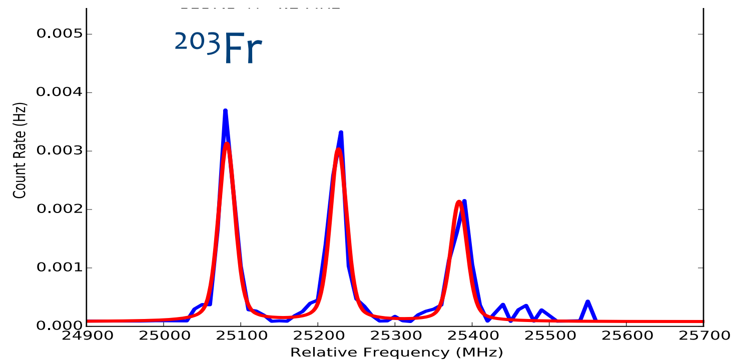
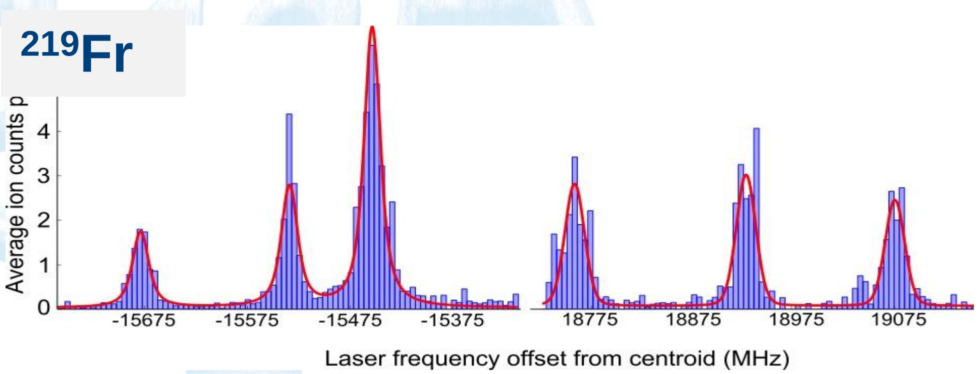
High resolution in CRIS



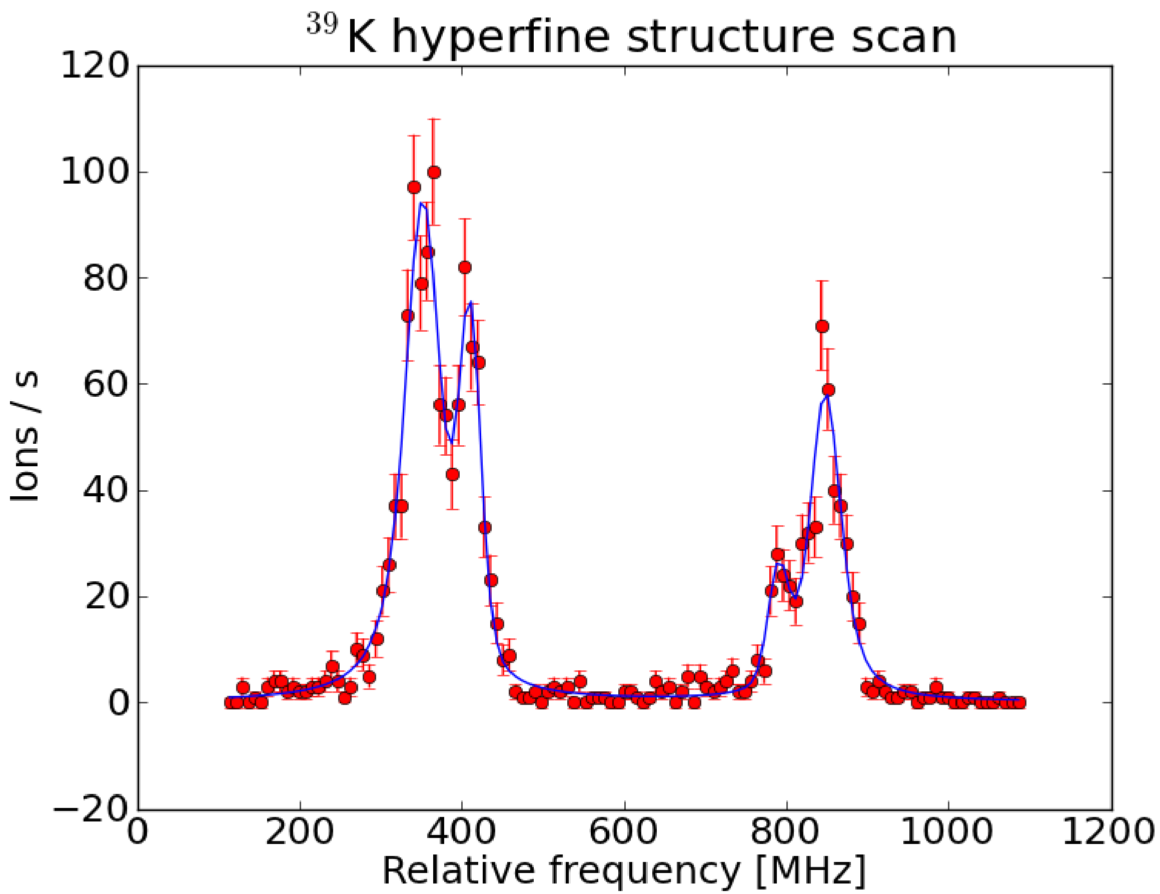






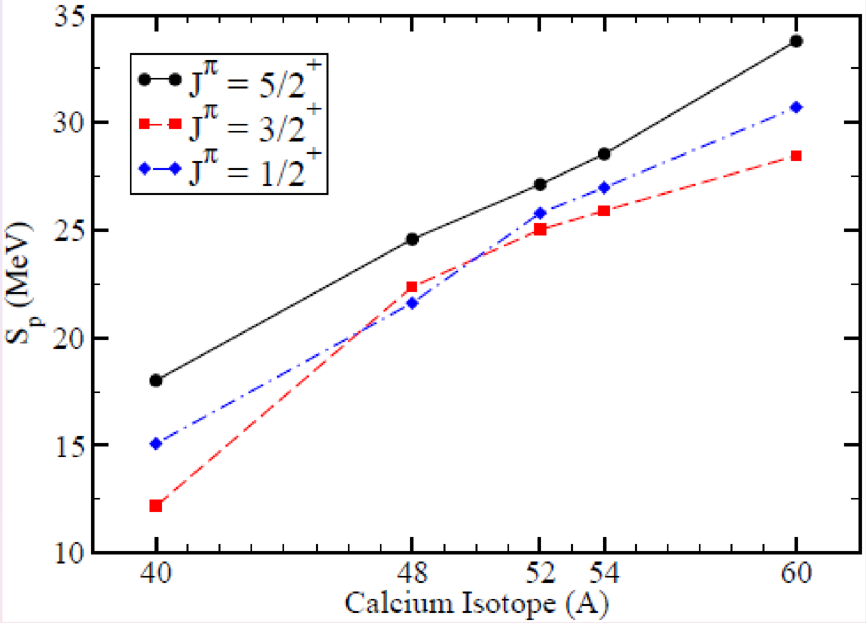


Another relevant result extracted from fitting the hyperfine structure was the Full width at half-maximum (FWHM) of the peaks FWHM = 44(5) MHz. This was already a significant improvement compared to the 1.5 GHz value obtained for the low-resolution francium data [5], providing confidence to perform high-resolution measurements on francium in November 2014. The main contribution to the FWHM value obtained from these offline measurements was the Doppler spread of the 5kV ion source beam. The estimated Doppler spread for a 5kV beam is 30.6 MHz, while the natural linewidth for this $2.6 \cdot 10^{-8}$ s transition is 6 MHz.



Given an original energy spread of about 1.5 eV and an acceleration voltage of 40 kV, the Doppler width can be reduced to 10 MHz, comparable to the natural line width.

$$\delta\nu_D = \nu_0 \frac{\delta E}{\sqrt{2eUMc^2}}.$$



- Proton separation energies $S_p = -E_\mu^- = E_\mu^{A-1} - E_0^A$ in ^{40,48,52,54,60}Ca.
- Low lying states in Potassium isotopes calculated using PA/PR-EOMCCSD with "bare" chiral interactions.
- Model space consists of 15 major harmonic oscillator shells with fixed oscillator frequency $\hbar\omega = 30$MeV.

	^{39}K		^{47}K	
J^π	E_{CC} (MeV)	E_{Exp} (MeV)	E_{CC} (MeV)	E_{Exp} (MeV)
$3/2^+$	0.00	0.00	0.00	0.00
$1/2^+$	2.90	2.52	-0.75	-0.36
$5/2^+$	5.84	4.51	2.22	3.00