Measurement of the changes in the mean-square charge radii of aluminium isotopes across $N = 20$

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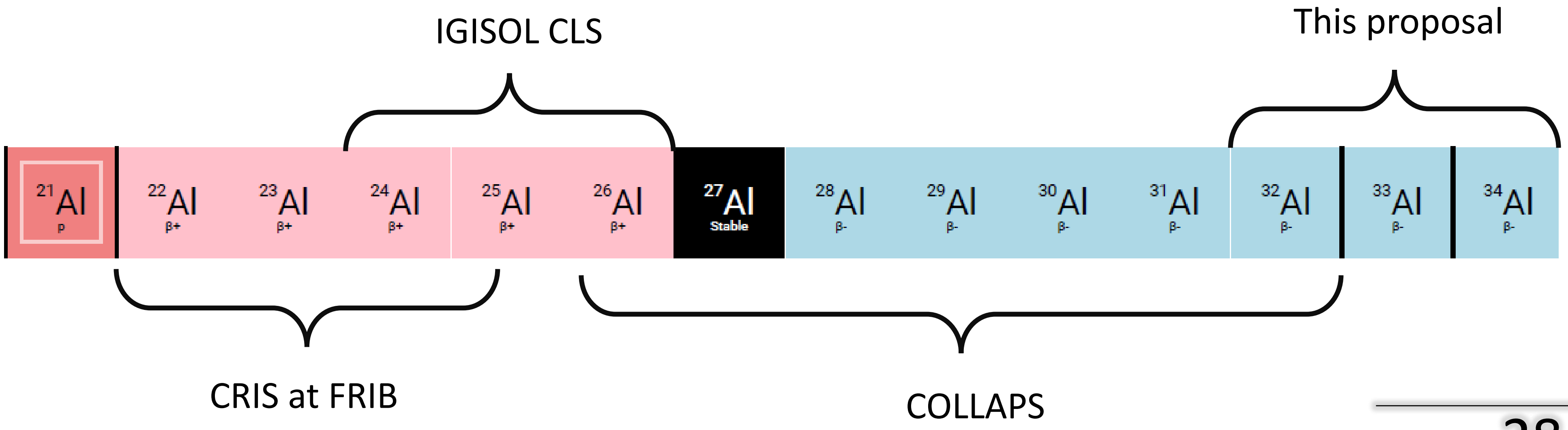
On behalf of the CRIS collaboration

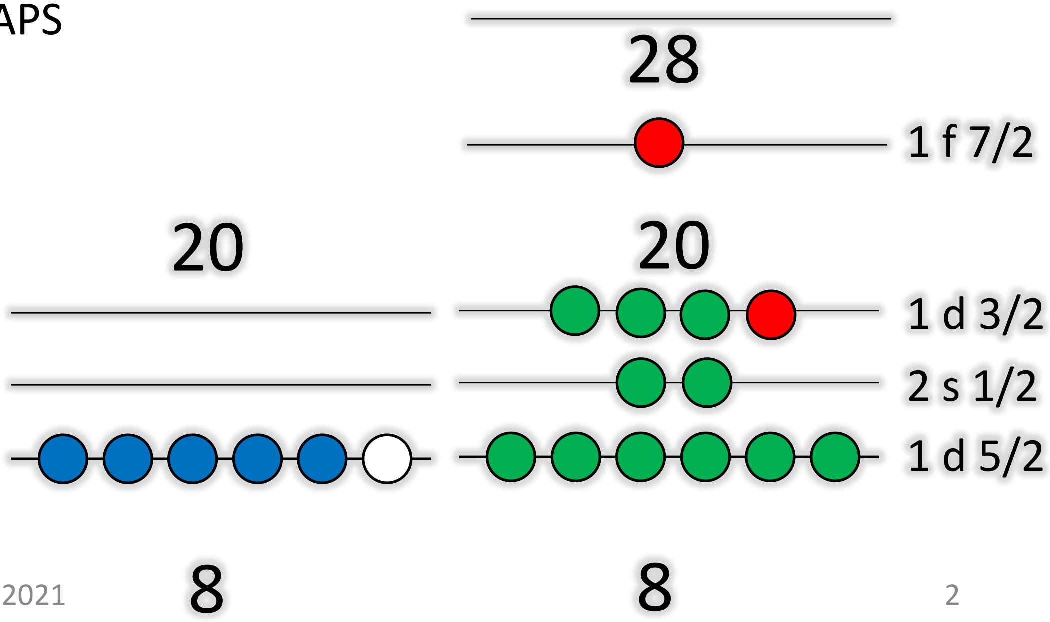
21.06.2021

Interest in the Al isotopes

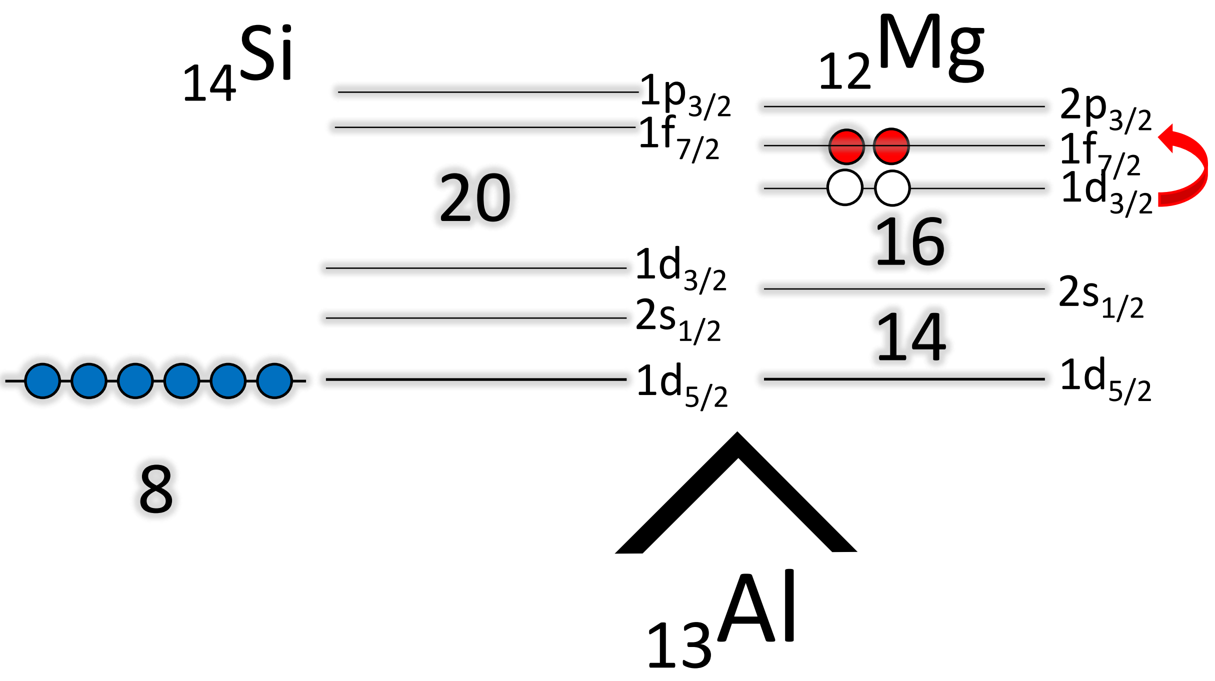


$^{26-32}$Al have been measured at **ISOLDE** by COLLAPS
$^{24-26}$Al proposed at **IGISOL** (collinear laser spectroscopy)
$^{22-23}$Al will be proposed at **FRIB** (CRIS)

We propose to measure the neutron-rich isotopes $^{32-34}$Al using the CRIS technique.



Island of inversion and *N*=20



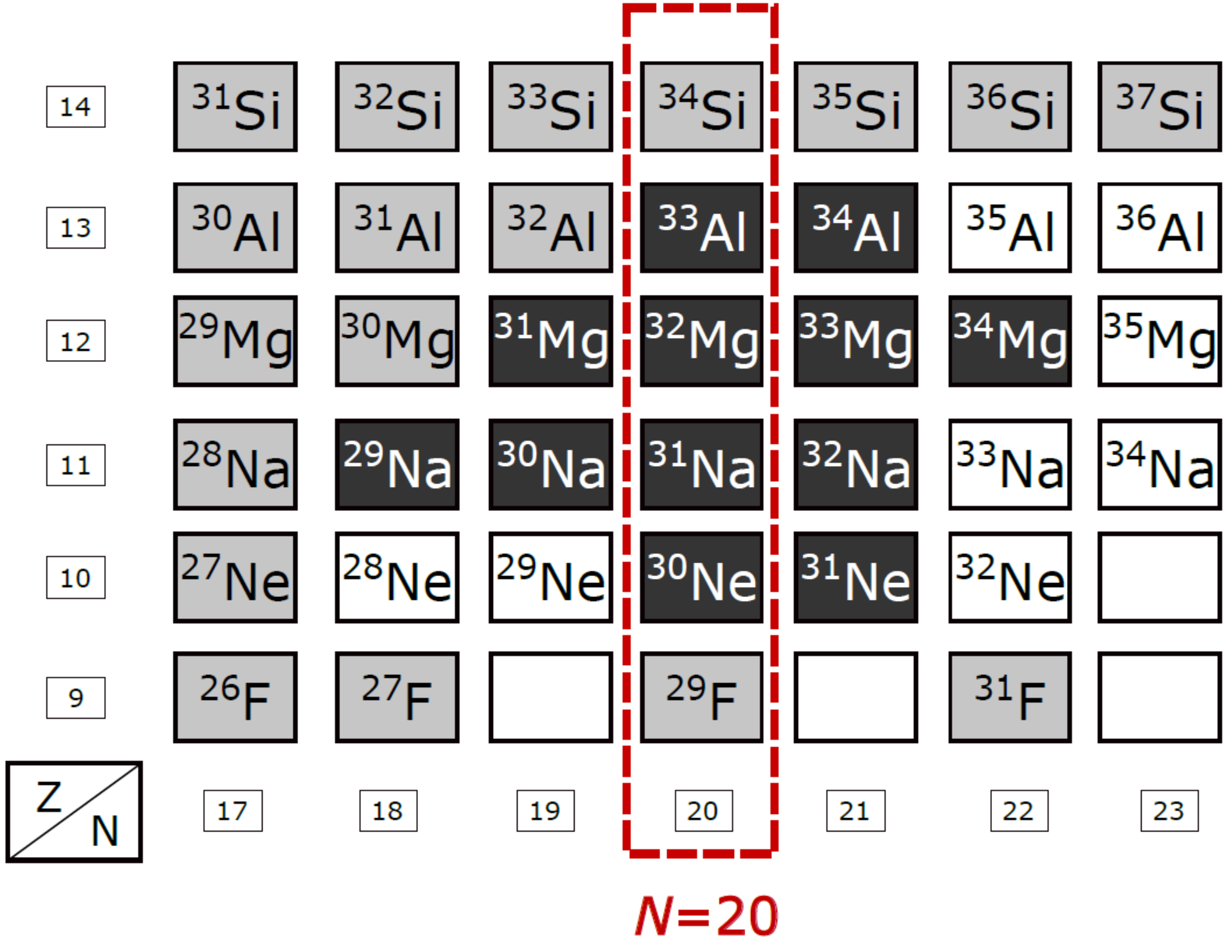


Figure: The island of inversion at N=20.

$^{33\text{-}34}$Al at the border of the island of inversion.

^{33}Al has a magic number of neutrons *N*=20.

Charge radii along N=20

No shell effect at the magic N=20 for Ar, K and Ca.

The study of Cl, S, P and Si is extremely challenging.

The charge radius of ^{32}Al was extracted with large uncertainties (7 MHz). However, the relatively low value may be an indication of the N=20 shell closure. [1]

Al is the next isotope which can be measured across N=20 without technical developments.

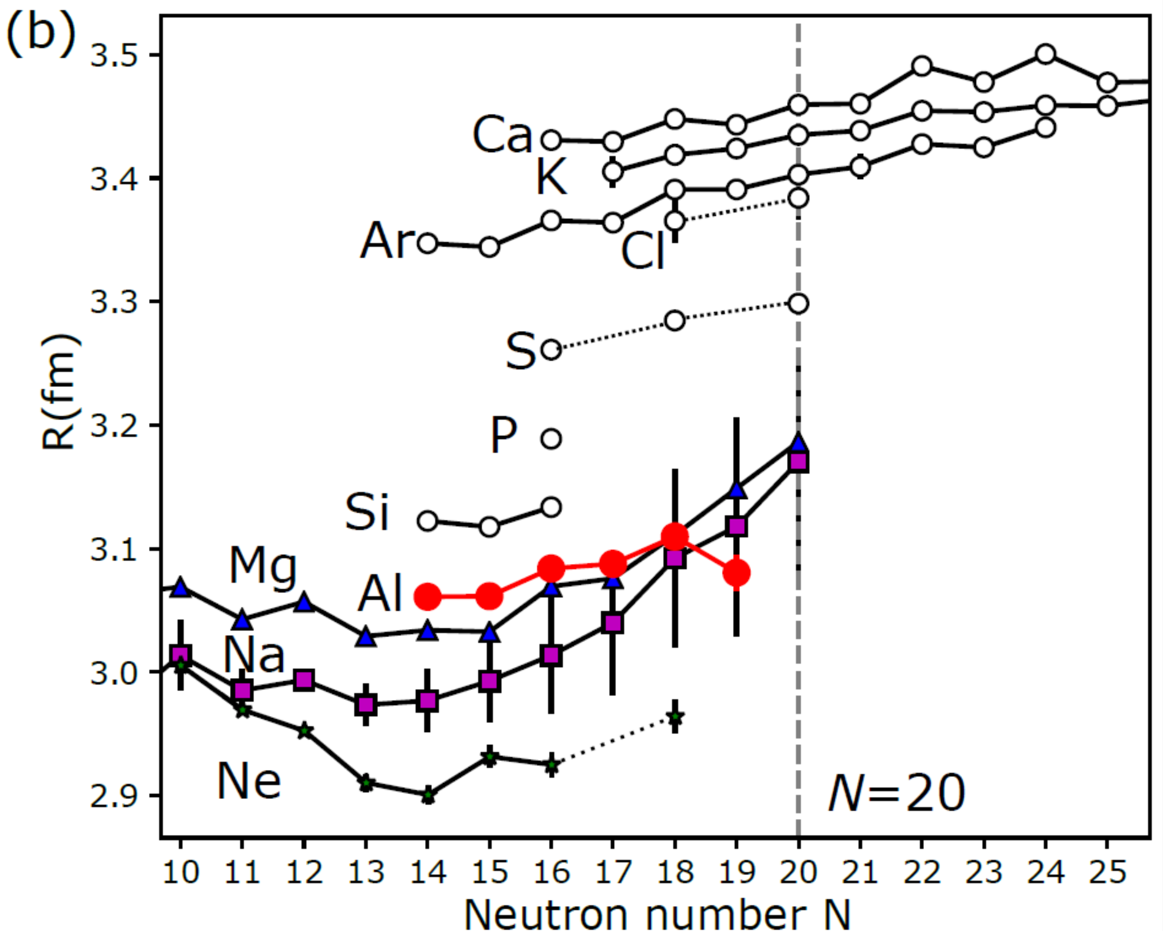


Figure: The charge radii around N=20.

[1] H. Heylen et al. Phys. Rev. C 103, 014318

Charge radii in the island of inversion

The charge radii are sensitive to structural changes in the Island of inversion and shell closures.

A striking correspondence is found between the nuclear charge radius and the neutron shell structure [1].

The onset of deformation is clear at N=19 in the Mg chain [1].

The radius of ^{32}Al is unexpectedly small [2].

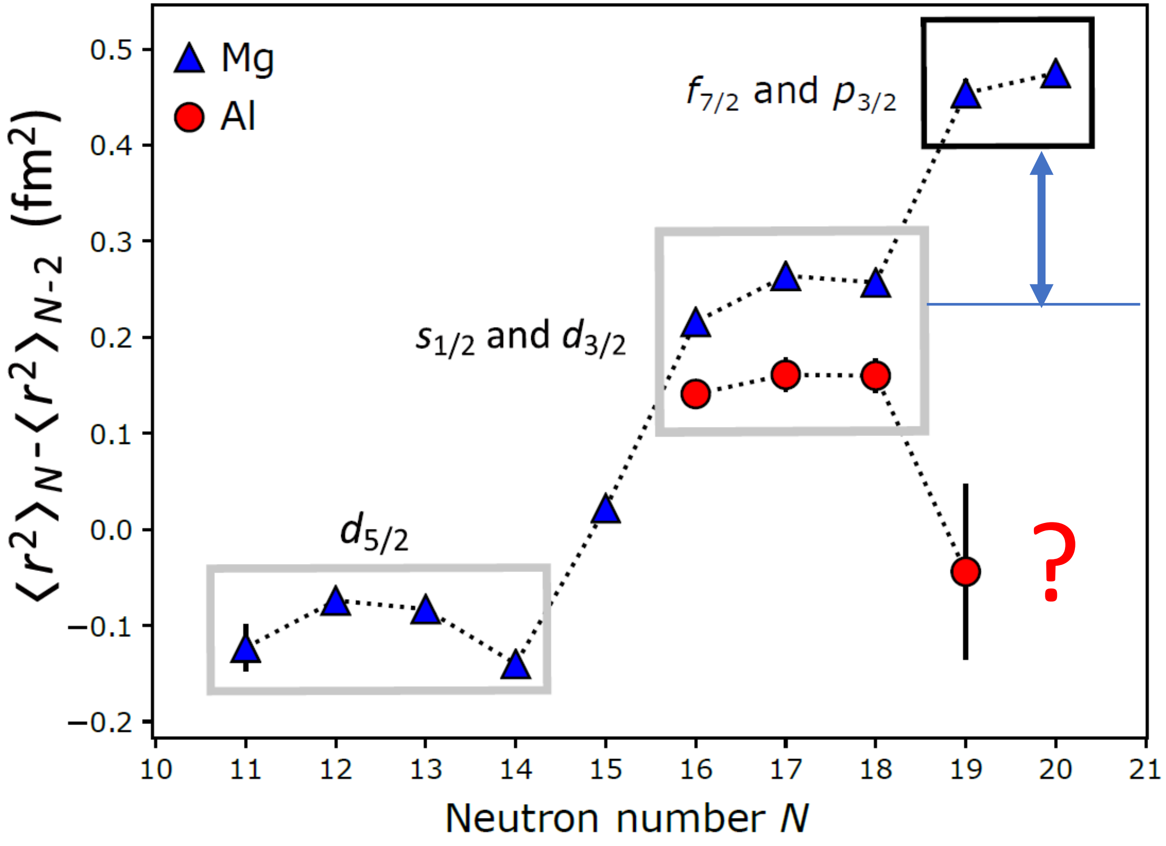
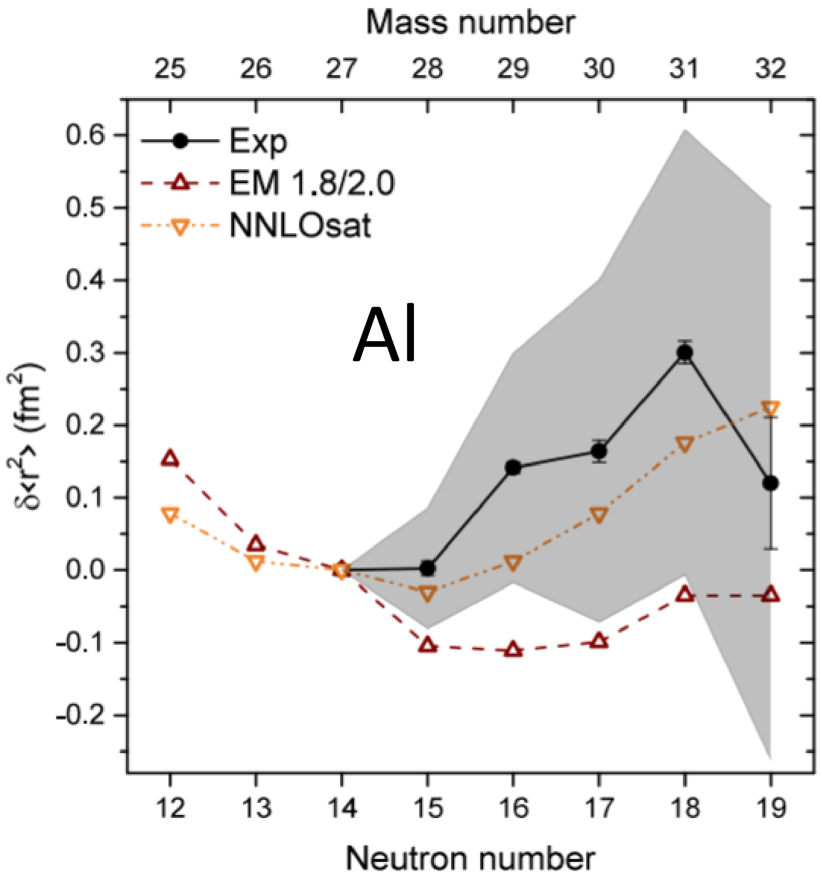


Figure: Differential charge radii of Mg and Al. Clear evidence for the onset of deformation at N=19 for Mg [1].

[1] D.T. Yordanov et al. Phys. Rev. Lett. 108, 042504
[2] H. Heylen et al. Phys. Rev. C 103, 014318

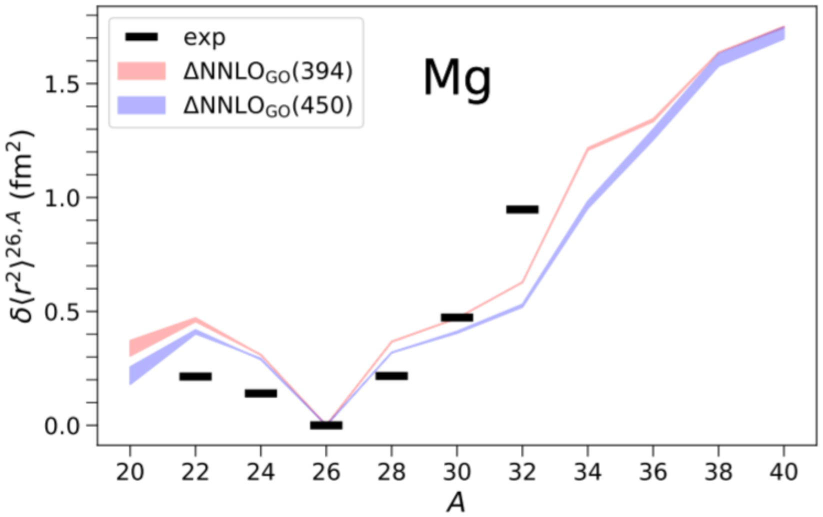
Theoretical models: VS-IMSRG and Coupled Cluster method

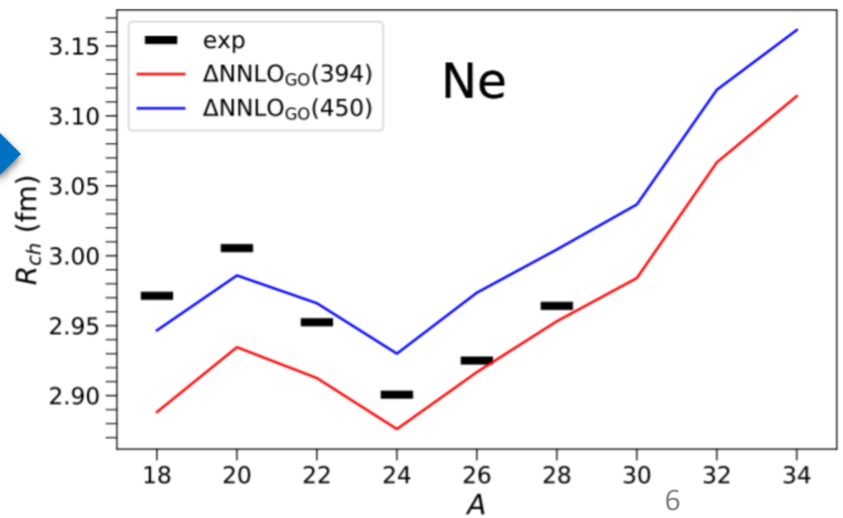


Both methods have been used in the region of the island of inversion.

VS-IMSRG canulations are readily available for Al. [1]

The CC [2] methods can used to calculate Al charge radii to the same approximation as in in the K chain.[3,4]





[1] H. Heylen et al. Phys. Rev. C 103, 014318
[2] S.J. Novario et al., Phys. Rev. C 102, 051303(R)
[3] A. Koszorus et al., Nature Physics 17, 439–443 (2021)
[4] G. Hagen, private communication

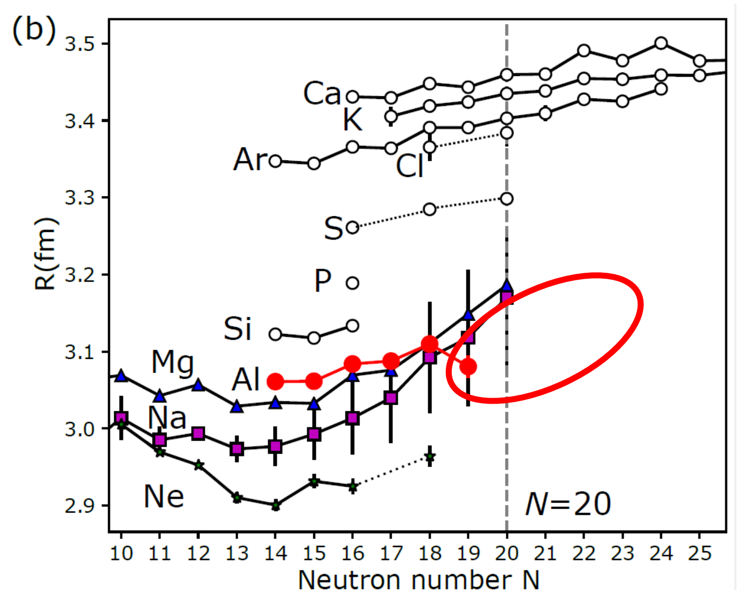
Open questions

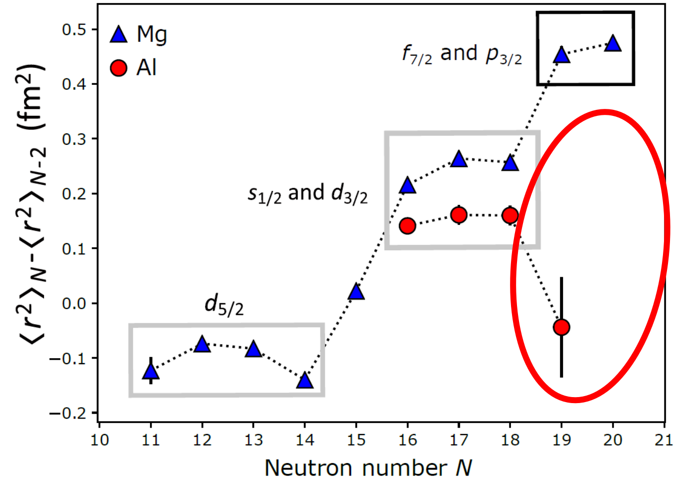
1. Investigate how the nuclear charge distribution evolves beyond *N*=20 in this uncharted territory?

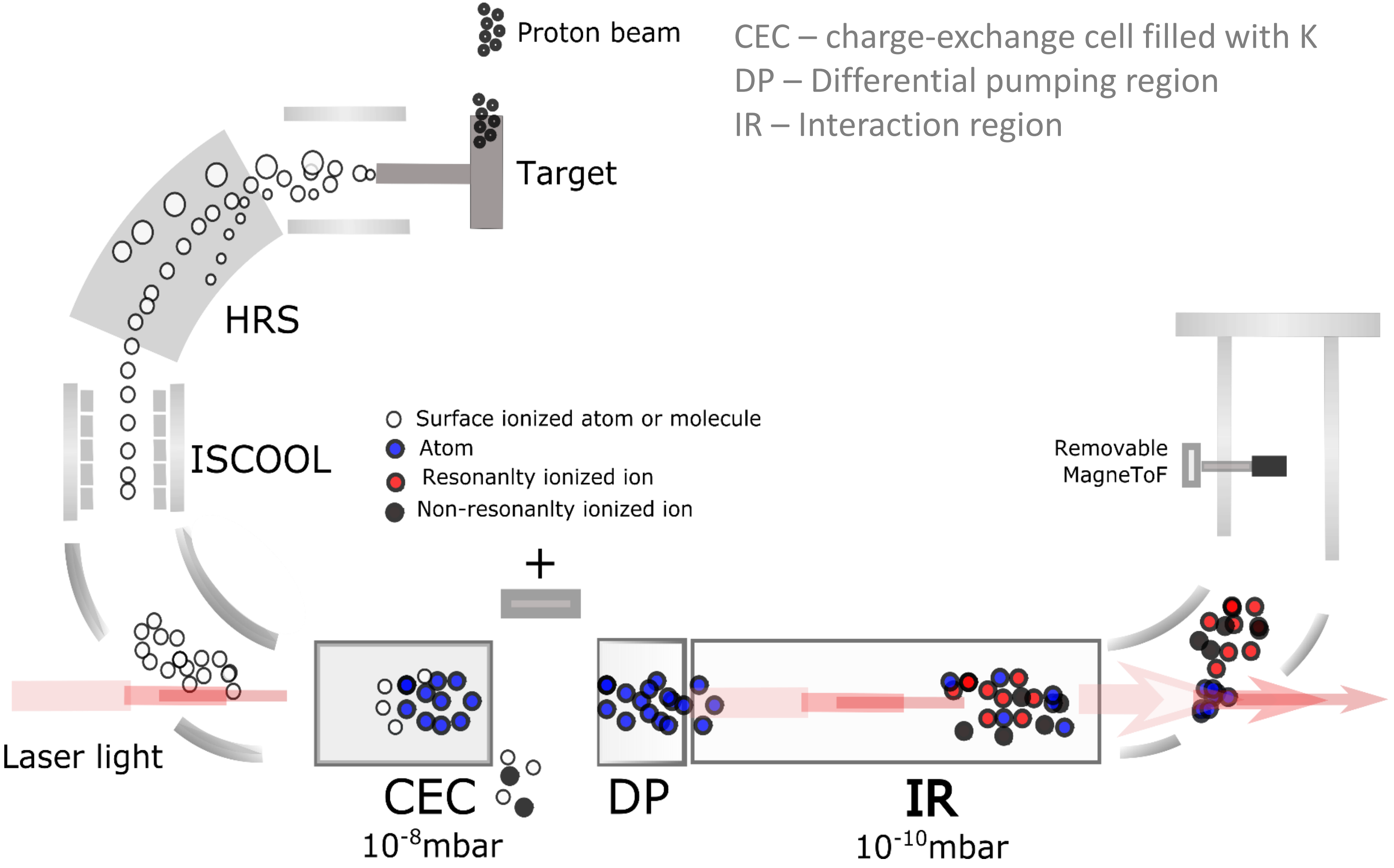
2. Is there a signature of deformation in the charge radii of $^{32\text{-}34}$Al isotopes? – Better understanding of the border of the island of inversion.

3. How do the experimental results compare to theoretical calculation?

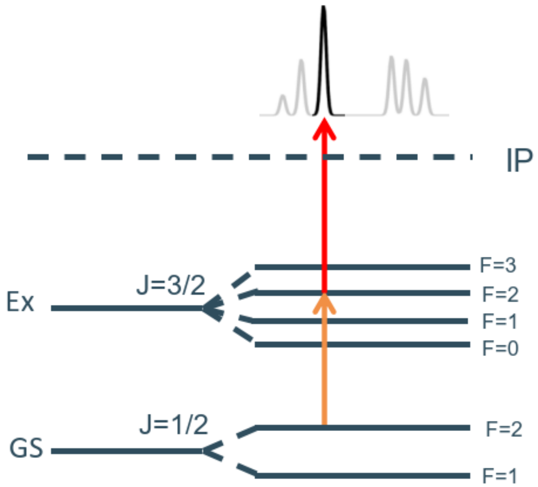
The precision measurement of the changes in the mean-square charge radius of $^{32\text{-}34}$Al provides answers to these questions.

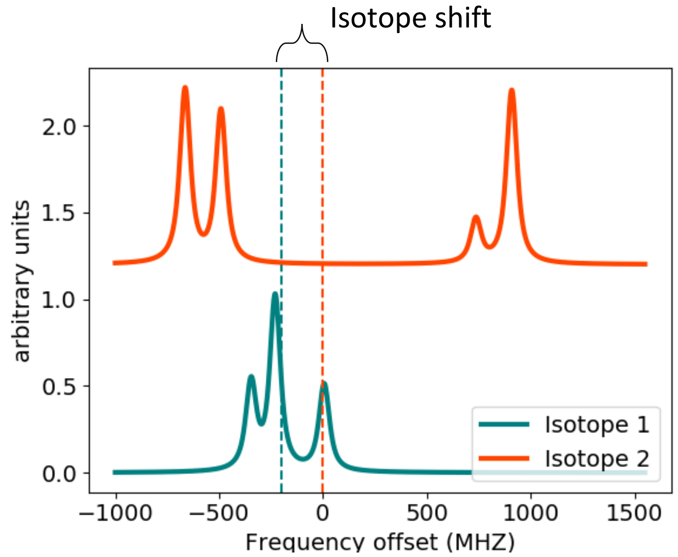




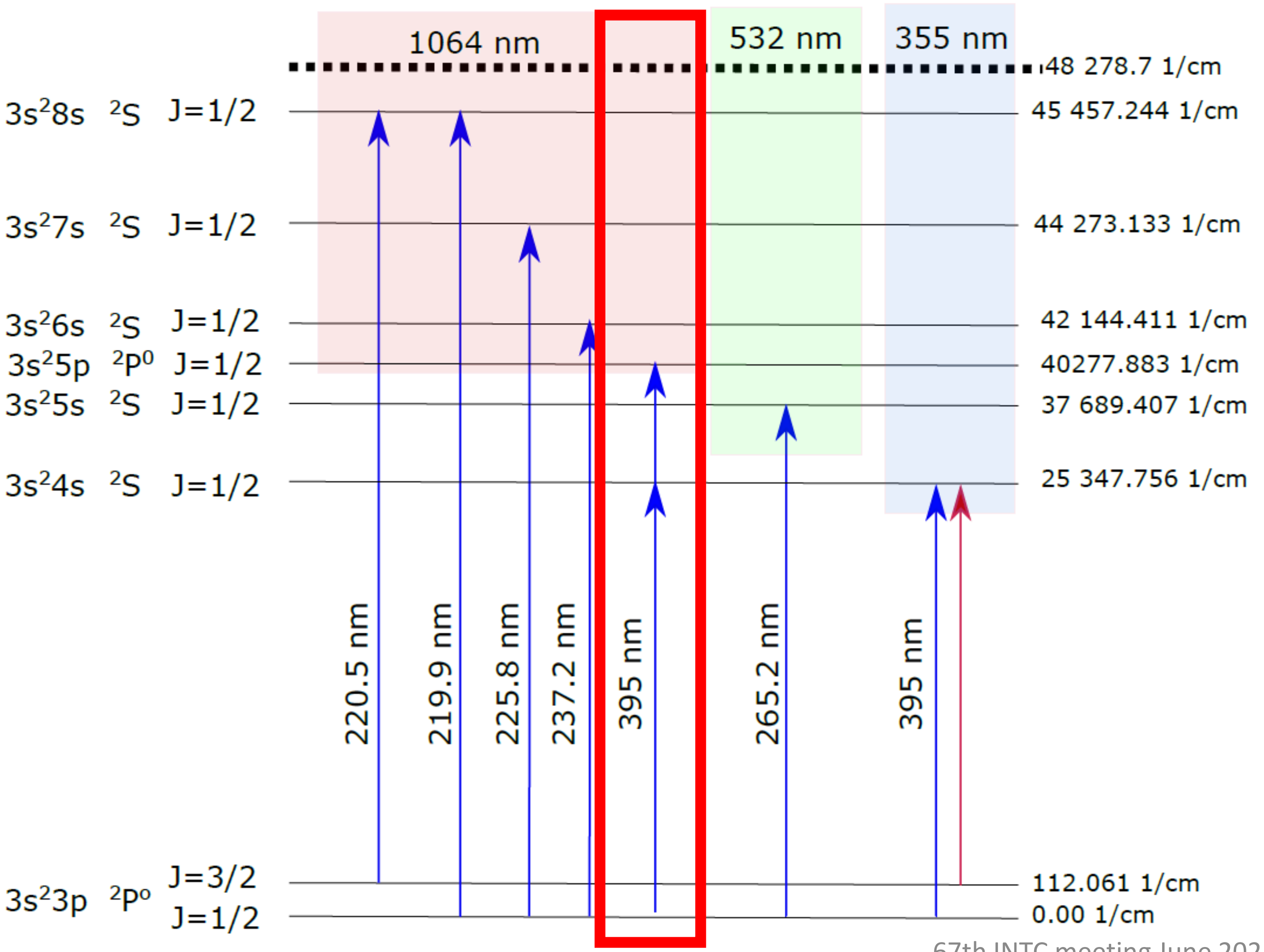


CEC – charge-exchange cell filled with K
DP – Differential pumping region
IR – Interaction region





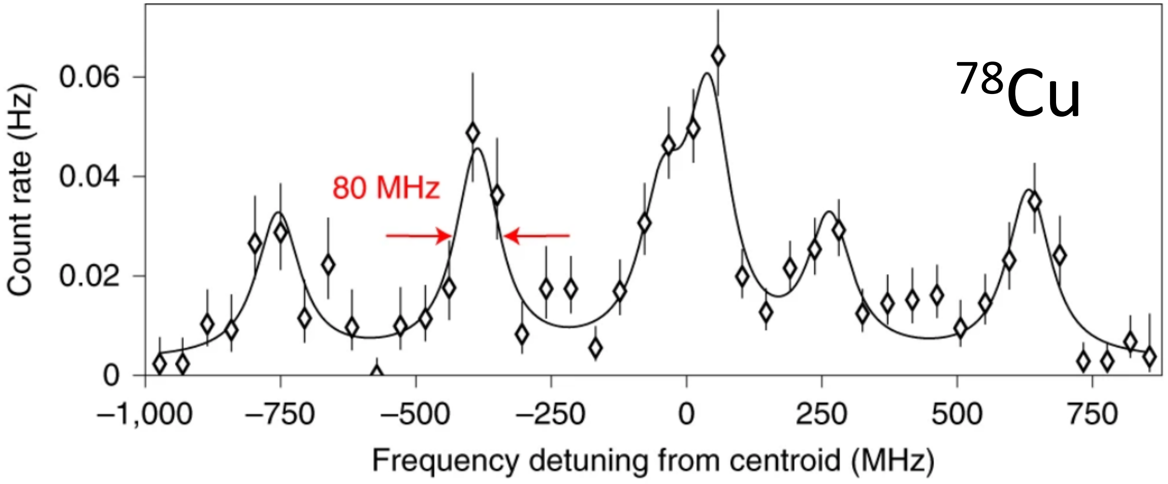
Isotope shift requires the precise measurement of the hfs of two isotopes.



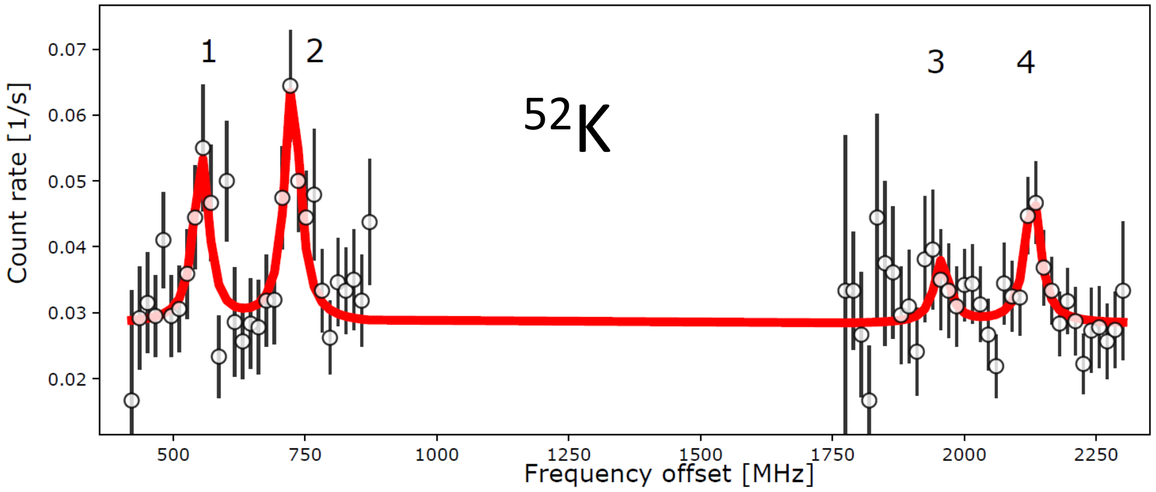
3 step resonance ionization scheme
395 nm + 670 nm + 1064 nm

All wavelengths can be produced by the existing lasers.

11 shifts requested for $^{33-34}$Al with yields of ~500 ions/s and >10 ions/s



20 ion/s produced [1]



360 ion/s produced [2]

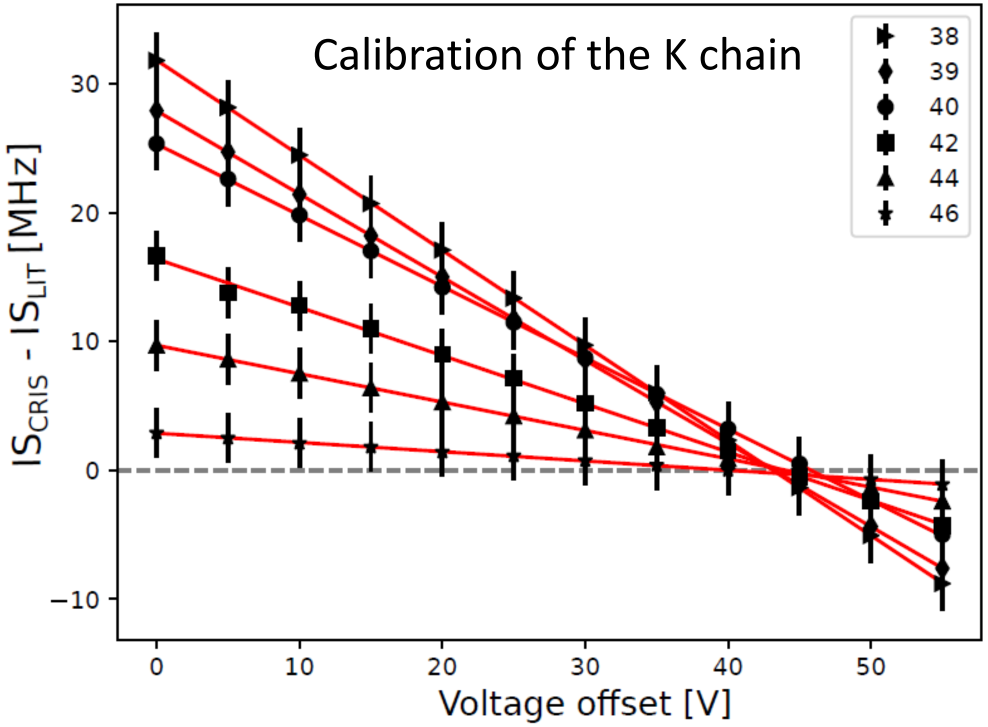
For the successful extraction of the changes in the mean-square charge radii of Al, a precision better than 2 MHz is required.

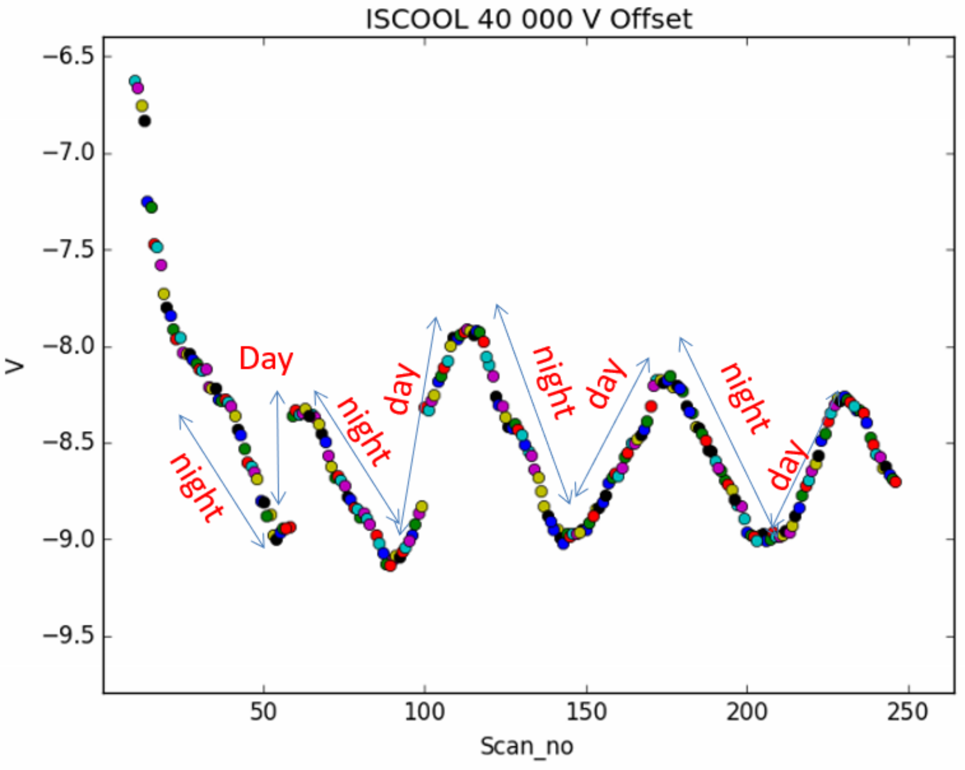
[1] R.P. de Groote et al., Nature Physics 16, 620–624 (2020)

[2] A. Koszorus et al., Nature Physics 17 439–443 (2021)

- Remeasure the $^{27\text{-}31}Al$ to calibrate the beam energy.
- Frequent reference measurements to monitor drifts.

2 shifts requested for $^{27\text{-}31}Al$ to get the systematics under control!



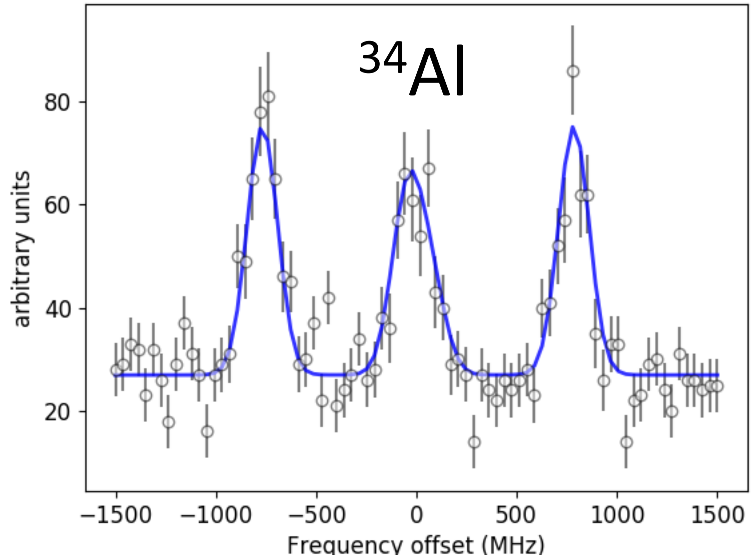


Shift request

Isotope	Predicted yields (ion/s)	Shifts
^{27}Al	Stable	0.5
$^{28-31}Al$	$>10^5$	2
^{32}Al	Not listed	1.5
^{33}Al	4.9×10^2	2
^{34}Al	>10	9
Beam tuning		1

In total 16 shifts.

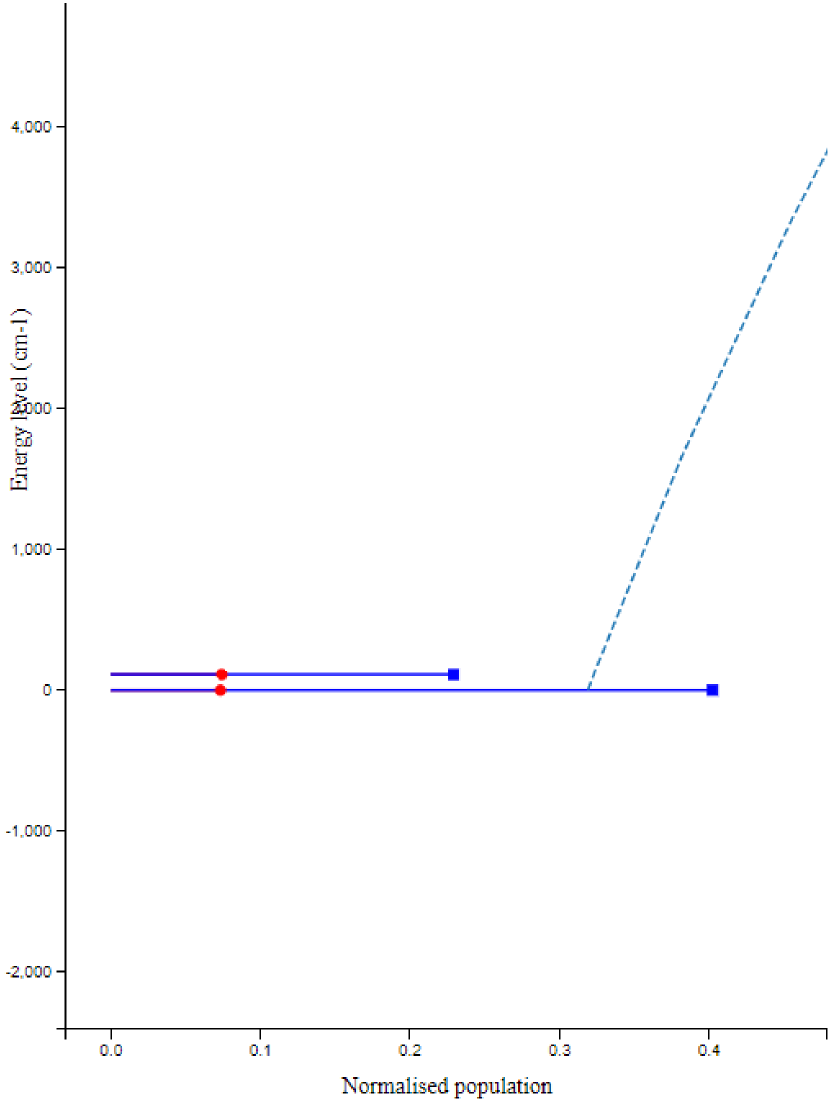
3 shifts → 5.3 MHz uncertainty



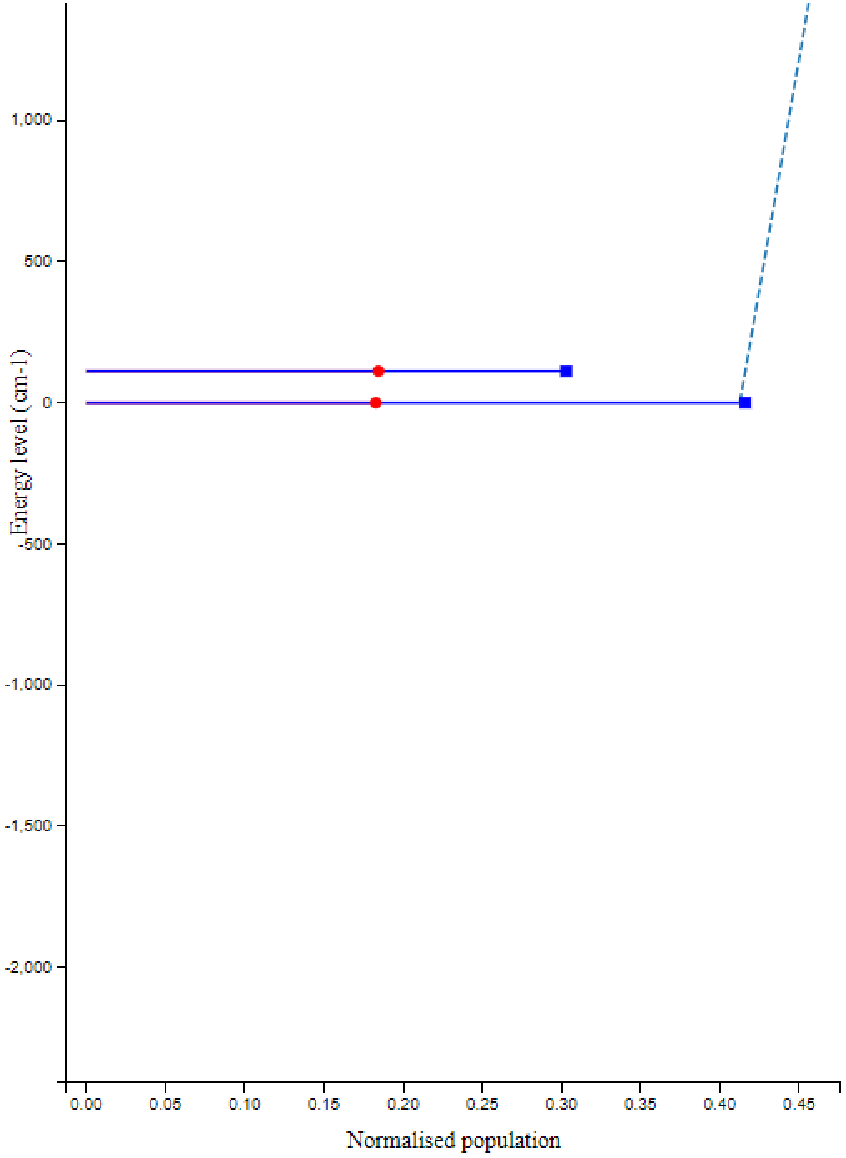
TAC comments:

The TAC does not foresee any issues with this proposal other than that the isotopes of concern are difficult to produce but this is well understood.

Thank you for your attention!



4,000
3,000
2,000
1,000
0
-1,000
-2,000
Energy level (cm-1)
0.0
0.1
0.2
0.3
0.4
Normalised population



1,000
500
0
-500
-1,000
-1,500
-2,000
Energy level (cm-1)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Normalised population

Charge radii of Al isotopes

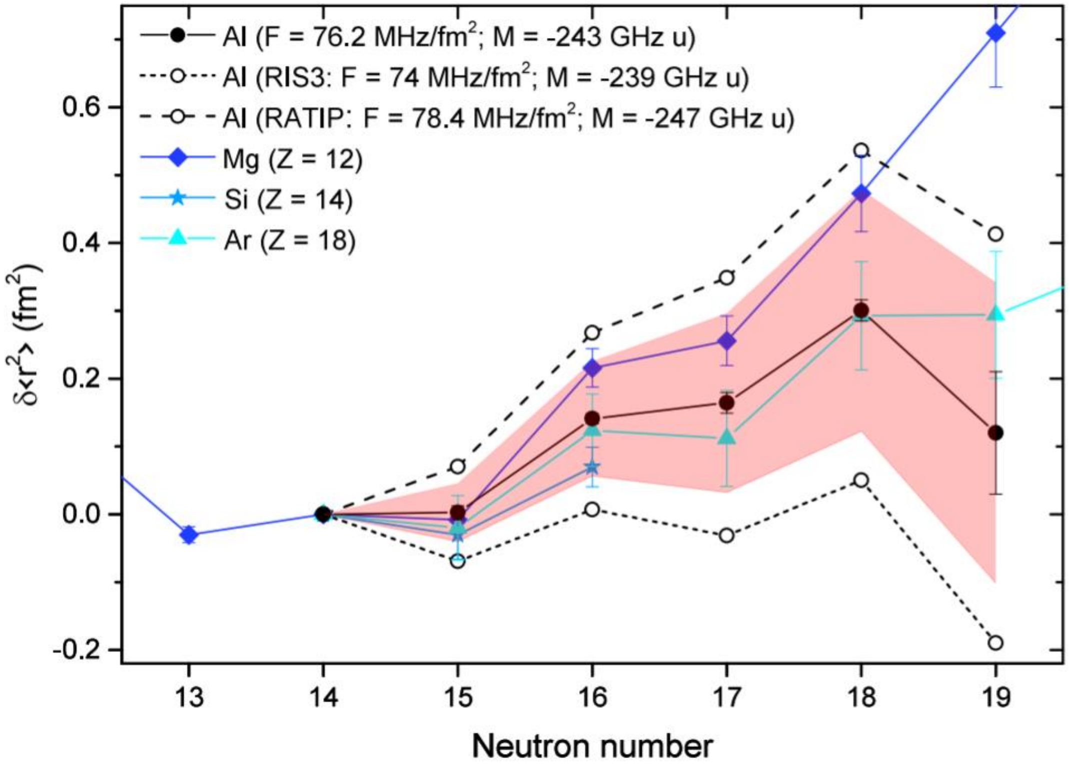


Figure: The charge radii of $^{27\text{-}32}$Al and the neighboring chains.

$^{26\text{-}32}$Al have been measured at **ISOLDE** by COLLAPS

The charge radius of ^{32}Al was extracted with large uncertainties (7 MHz). However, the relatively low value may be an indication of the *N*=20 shell closure. [1]

Measurements with higher experimental precision are required.

[1] H. Heylen et al. Phys. Rev. C 103, 014318

CRIS technique

Changes in the mean-square charge radii

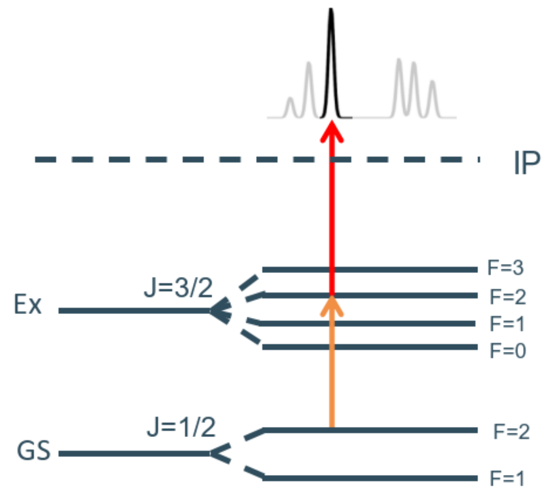
Isotope shift

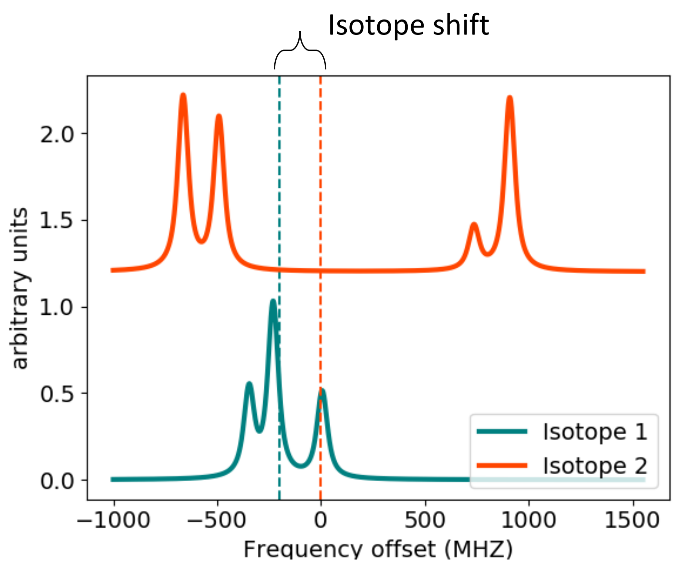
$$\delta < r^2 > = \frac{1}{F}\left(\frac{m_A - m_{A'}}{m_A m_{A'}} K - \delta\nu\right)$$

F and *K* and atomic parameters.

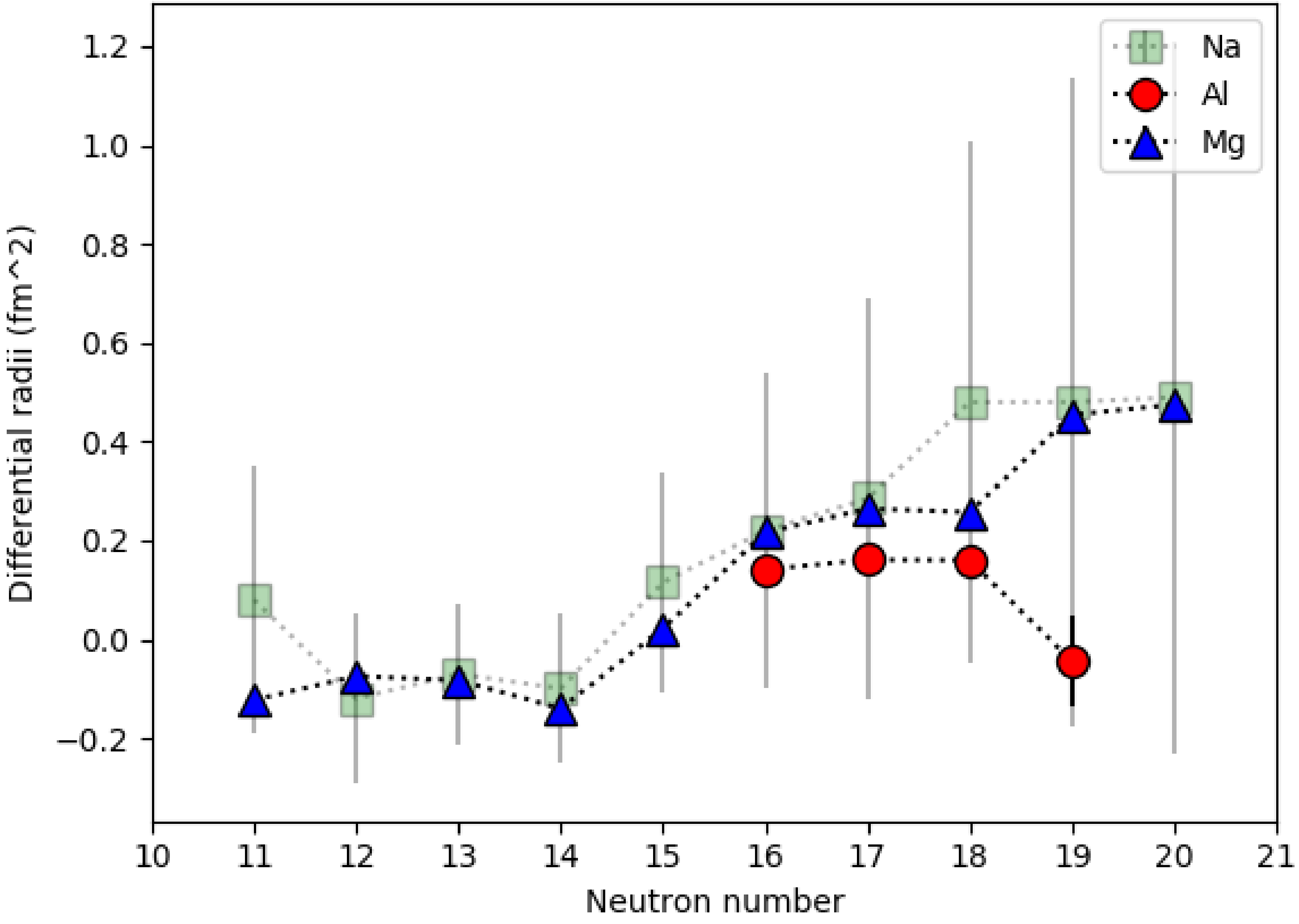
F is sensitive to the chare radius!

Light isotopes have small *F*. ~ 70 MHz/fm^2 for Al
→ High experimental precision is required for $\delta\nu$ to extraction of the $\delta < r^2 >$.





Isotope shift requires the precise measurement of the hfs of two isotopes.

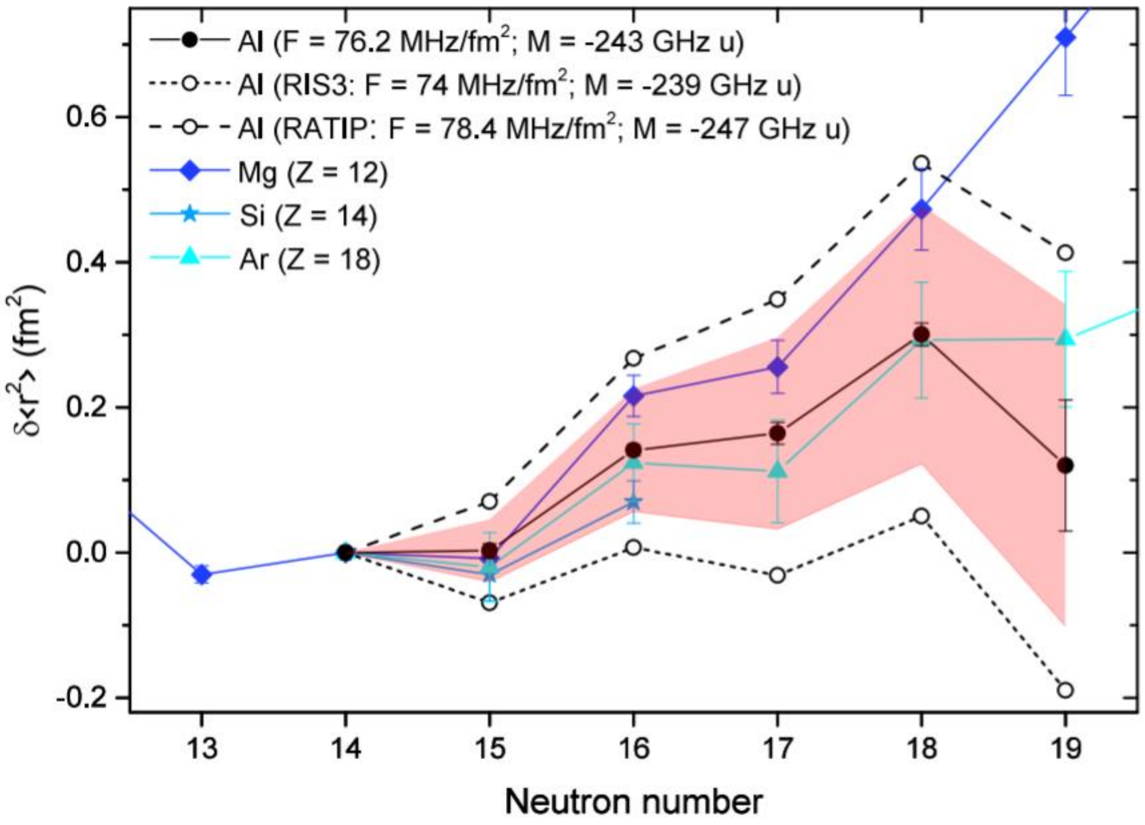


Na
Al
Mg
Differential radii (fm^2)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
10
11
12
13
14
15
16
17
18
19
20
21
Neutron number

CRIS scheme

219.9150	1.75e+06	0.000	45 457.244	$3s^2 3p$	$^2P°$	$^1/_2$	$3s^2 8s$	^2S	$^1/_2$
220.4590	3.49e+06	112.061	45 457.244	$3s^2 3p$	$^2P°$	$^3/_2$	$3s^2 8s$	^2S	$^1/_2$
225.7999	3.77e+06	0.000	44 273.133	$3s^2 3p$	$^2P°$	$^1/_2$	$3s^2 7s$	^2S	$^1/_2$
237.2070	5.76e+06	0.000	42 144.411	$3s^2 3p$	$^2P°$	$^1/_2$	$3s^2 6s$	^2S	$^1/_2$
265.2484	1.42e+07	0.000	37 689.407	$3s^2 3p$	$^2P°$	$^1/_2$	$3s^2 5s$	^2S	$^1/_2$

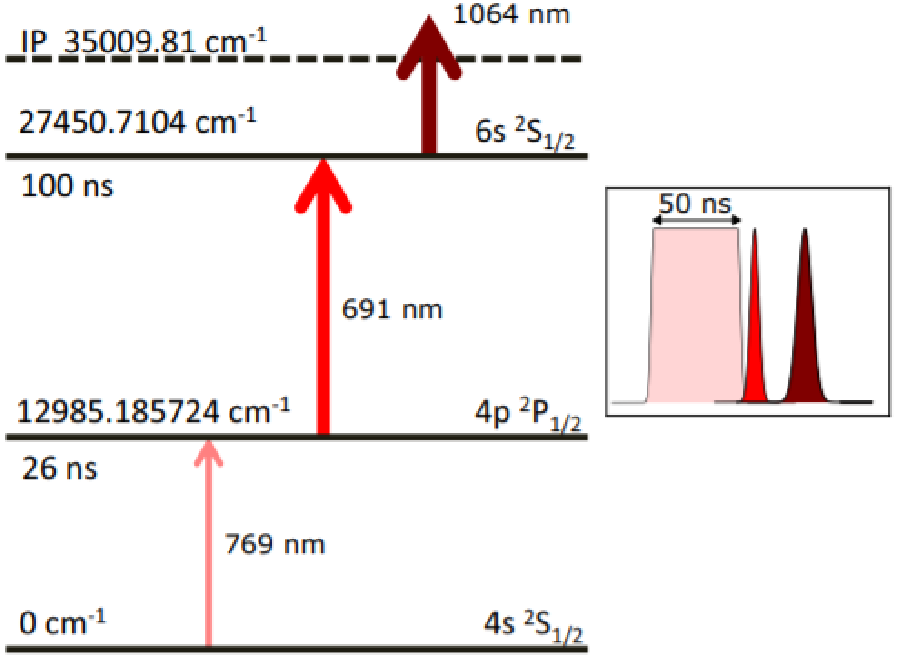
394.40058	4.99e+07	0.000	25 347.756	$3s^2 3p$	$^2P°$	$^1/_2$	$3s^2 4s$	^2S	$^1/_2$
396.15200	9.85e+07	112.061	25 347.756	$3s^2 3p$	$^2P°$	$^3/_2$	$3s^2 4s$	^2S	$^1/_2$



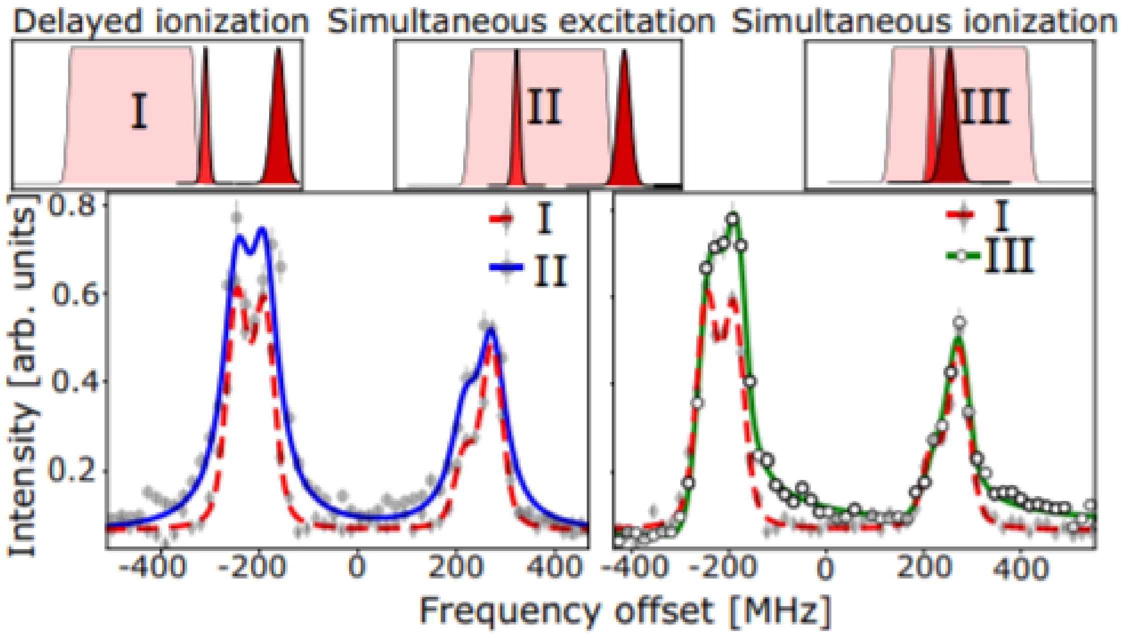
multiconfiguration DiracHartree-Fock framework for the atomic parameters

Ab initio atomic calculations are now possible with coupled-cluster theory.

This will result in more accurate atomic parameters.



IP 35009.81 cm-1
1064 nm
27450.7104 cm-1
6s 2S1/2
100 ns
691 nm
50 ns
12985.185724 cm-1
4p 2P1/2
26 ns
769 nm
0 cm-1
4s 2S1/2



Delayed ionization
Simultaneous excitation
Simultaneous ionization
I
II
III
Intensity [arb. units]
0.8
0.6
0.4
0.2
-400
-200
0
200
400
Frequency offset [MHz]