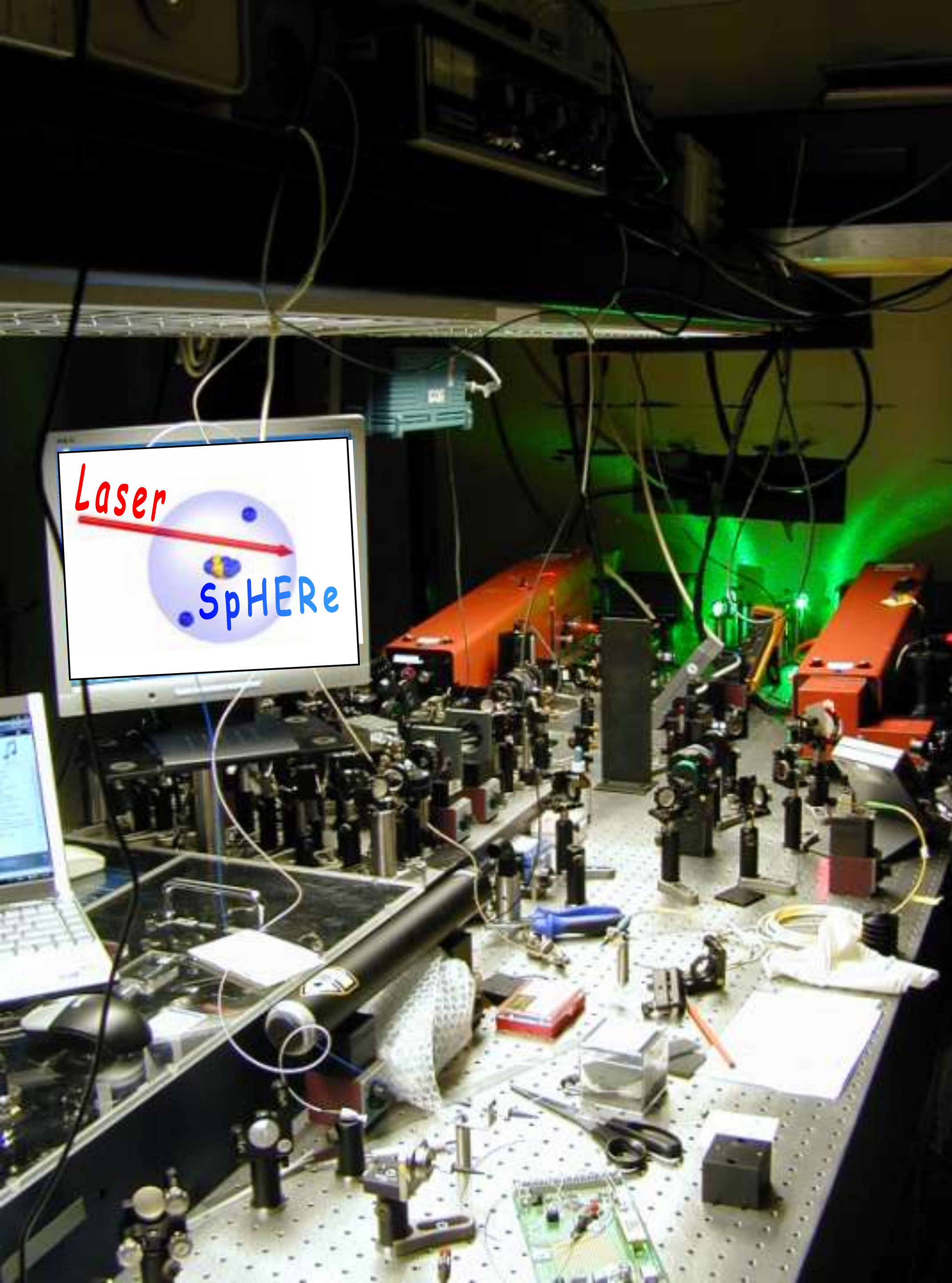

High precision atomic data for halo nuclei and related nuclear structure

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TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

ICAMDATA : International Conference on Atomic and Molecular Data and Their Applications

Experiments: Challenges and Solutions

Nuclear Structure Conclusions from $\delta\langle r^2\rangle$

Absolute Charge Radii

Nuclear Moments

Outlook (What's next ?)

Challenges in the Spectroscopy of Halo Nuclei

$$\delta\nu^{A,A'} = \nu_{A'} - \nu_{A} = F\,\delta\langle r^2\rangle^{A,A'} + M\,\frac{m_{A'} - m_{A}}{m_{A'} m_{A}}$$

Example: Helium Isotopes:

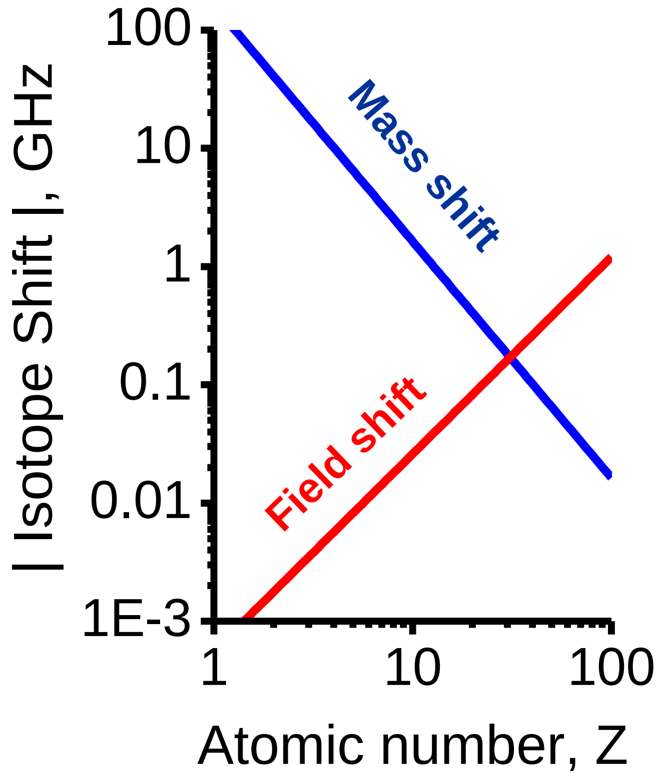
Mass Shift ^{4}He-^{8}He: ~ 64 700 000 kHz
Field Shift ^{4}He-^{8}He: ~ 1 000 kHz
IS Accuracy: ~ 100 kHz
~ 3×10^{-6}
~ Doppler Shift @ 4 cm/s

Single Photon Recoil (20 cm/s) 430 kHz
Difference ^{4}He-^{8}He: 215 kHz

External degrees of freedom must be under control or the method must be insensitive to them.

Lifetime (^{11}Li) ~ 8 ms

Production Rate (^{11}Li, ^{12}Be) ~ 10.000 s^{-1}

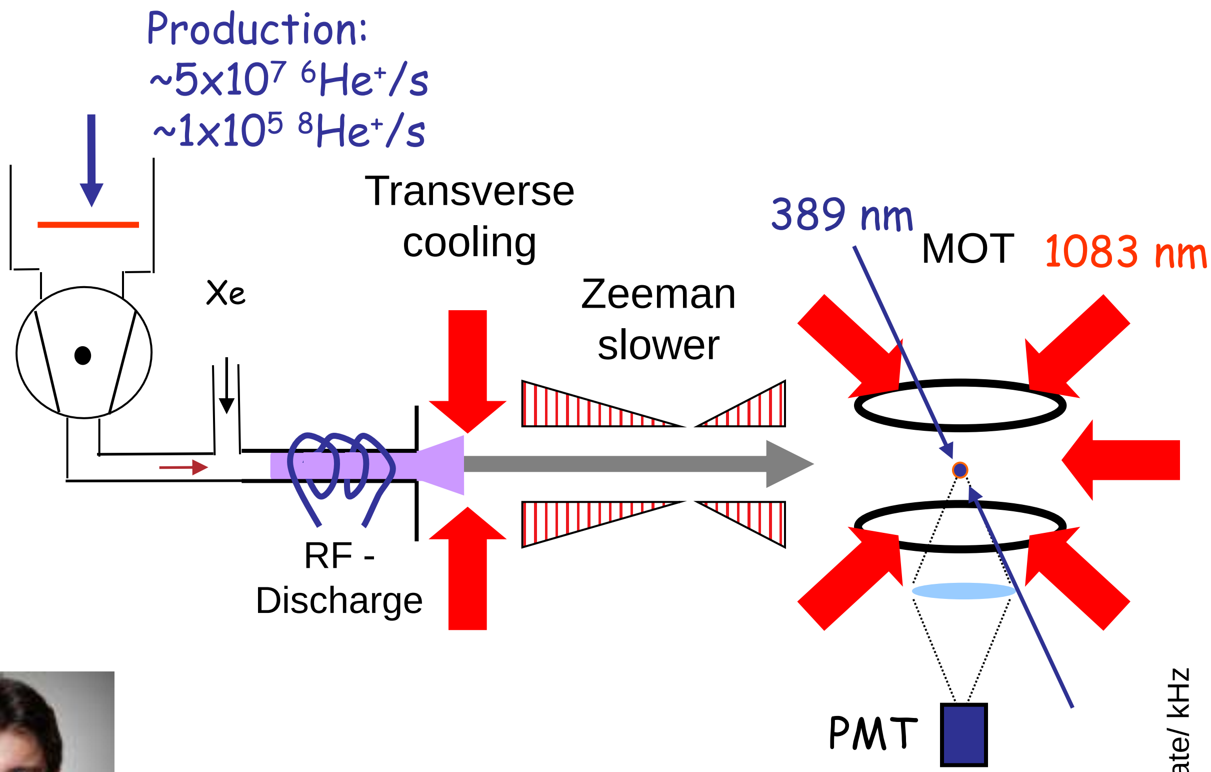


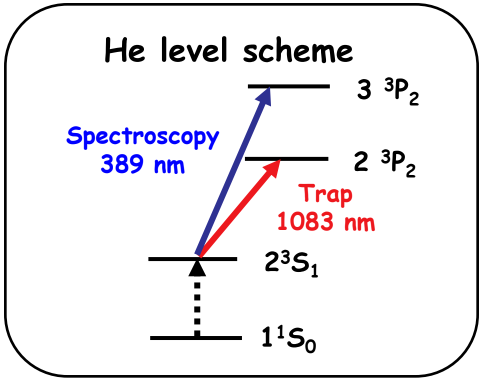
Spectroscopic Techniques must be:

Accurate
Fast
Efficient (Sensitive)

(1) Helium: Cold Atoms in a Magneto-Optical Trap

Atom Trap Setup



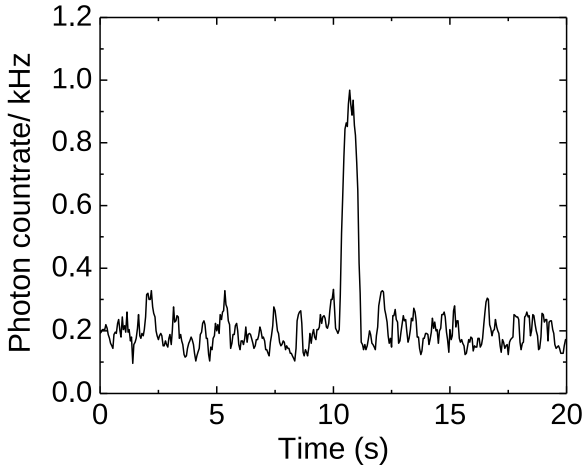


Presidential Early Career Award, 2012

Capture efficiency 1x10^{-7}

Trap
~5 ^{6}He/s,
~30 ^{8}He/hr

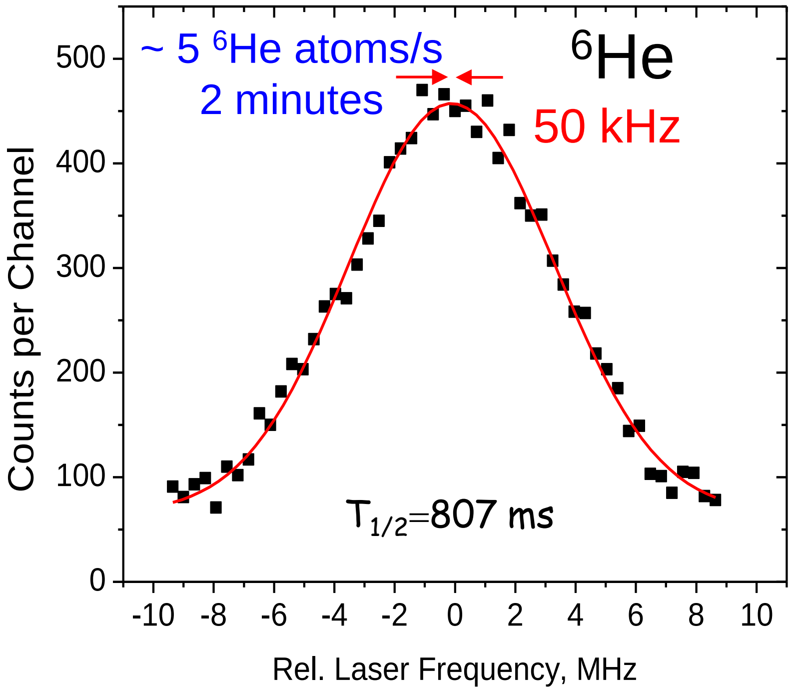
One trapped ^{6}He atom

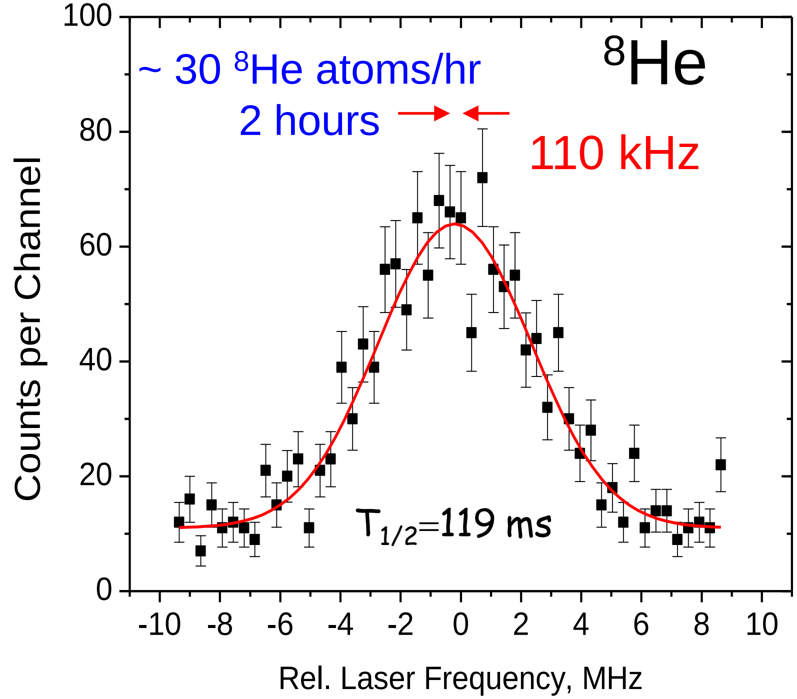


P: Mueller et al., PRL 99, 252501 (2007)

(1) Helium: Sample Spectra

P: Mueller et al., PRL 99, 252501 (2007)



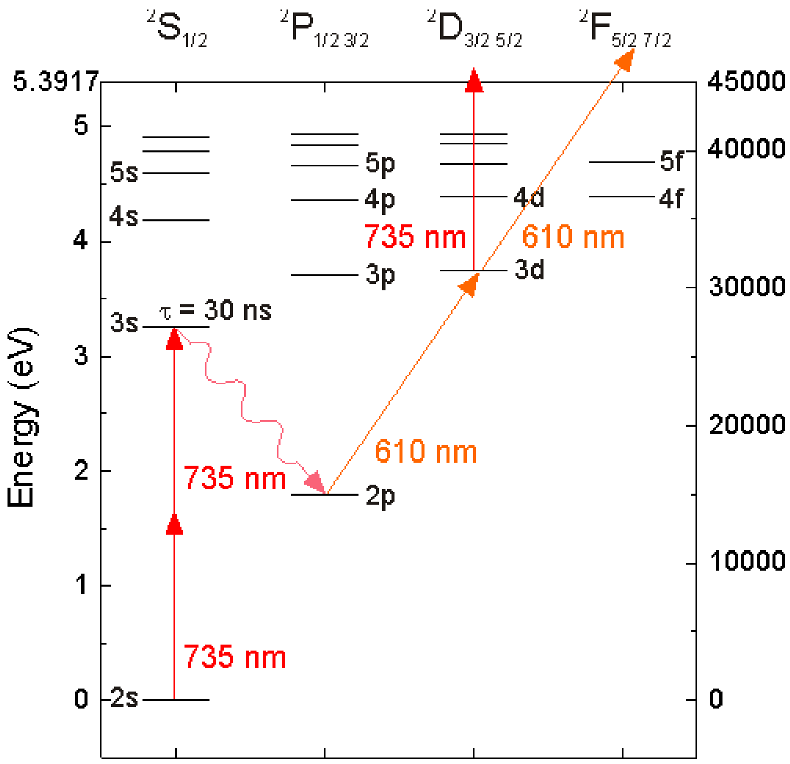


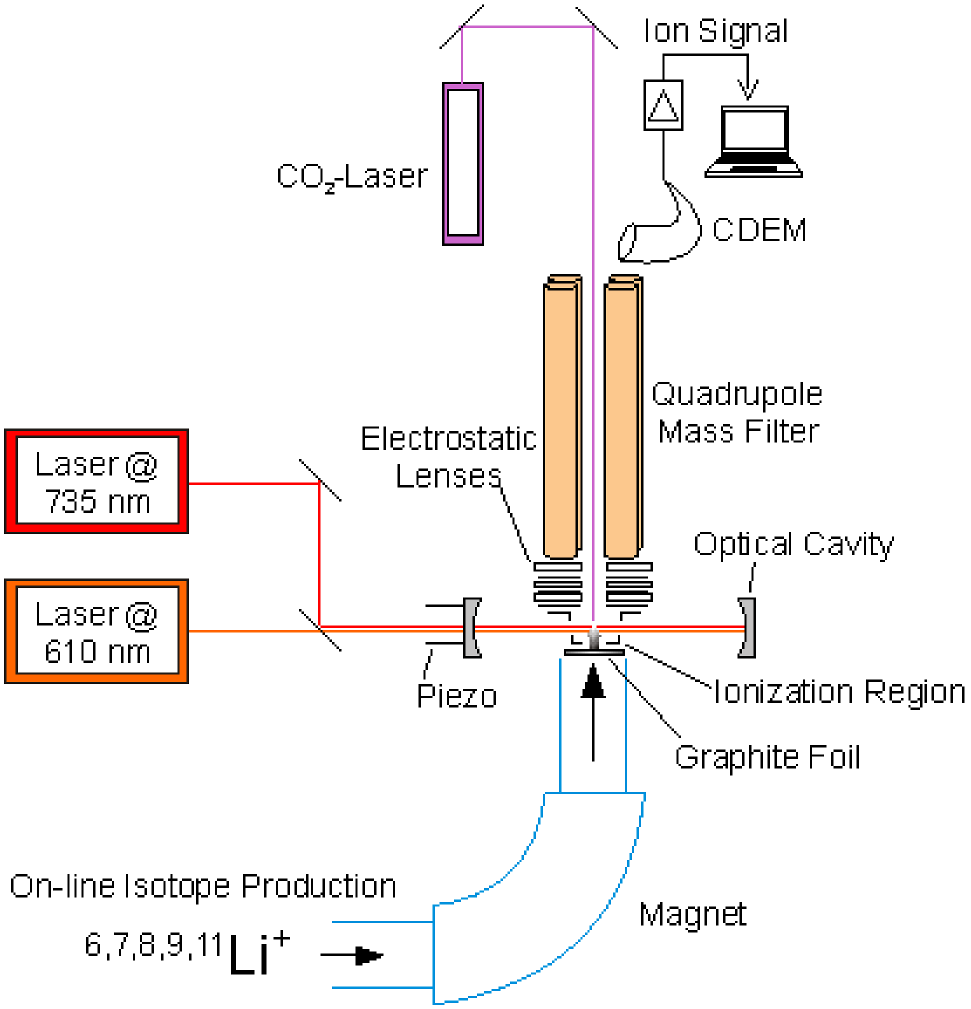
Transition	$\delta\nu^{A,4}$	$\delta\nu^{A,4}_{MS}$	$\delta\nu^{A,4}_{FS}$
^{8}He $2^3S_1 \rightarrow 3^3P_1$	64 701.129(73)	64 702.0982	−0.969(73)
^{8}He $2^3S_1 \rightarrow 3^3P_2$	64 701.466(52)	64 702.5086	−1.043(52)
Mean + nucl. pol.			−1.020(42){64}
^{6}He $2^3S_1 \rightarrow 3^3P_0$	43 194.740(37)	43 196.1573	−1.417(37)
^{6}He $2^3S_1 \rightarrow 3^3P_1$	43 194.483(12)	43 195.8966	−1.414(12)
^{6}He $2^3S_1 \rightarrow 3^3P_2$	43 194.751(10)	43 196.1706	−1.420(10)
Mean + nucl. pol.			−1.431(8){31}
^{6}He $2^3S_1 \rightarrow 3^3P_2$	43 194.772(33)	43 196.1706	−1.399(33){50}
Mean			−1.430(8){31}

Brodeur et al. PRL 108 052504 (2012)

(2) Lithium: Two-Photon Spectroscopy

Experimentally required:
Accuracy of ~ 200 kHz
High sensitivity : $\varepsilon > 10^{-4}$
Fast technique: $T_{1/2} \sim 8$ ms



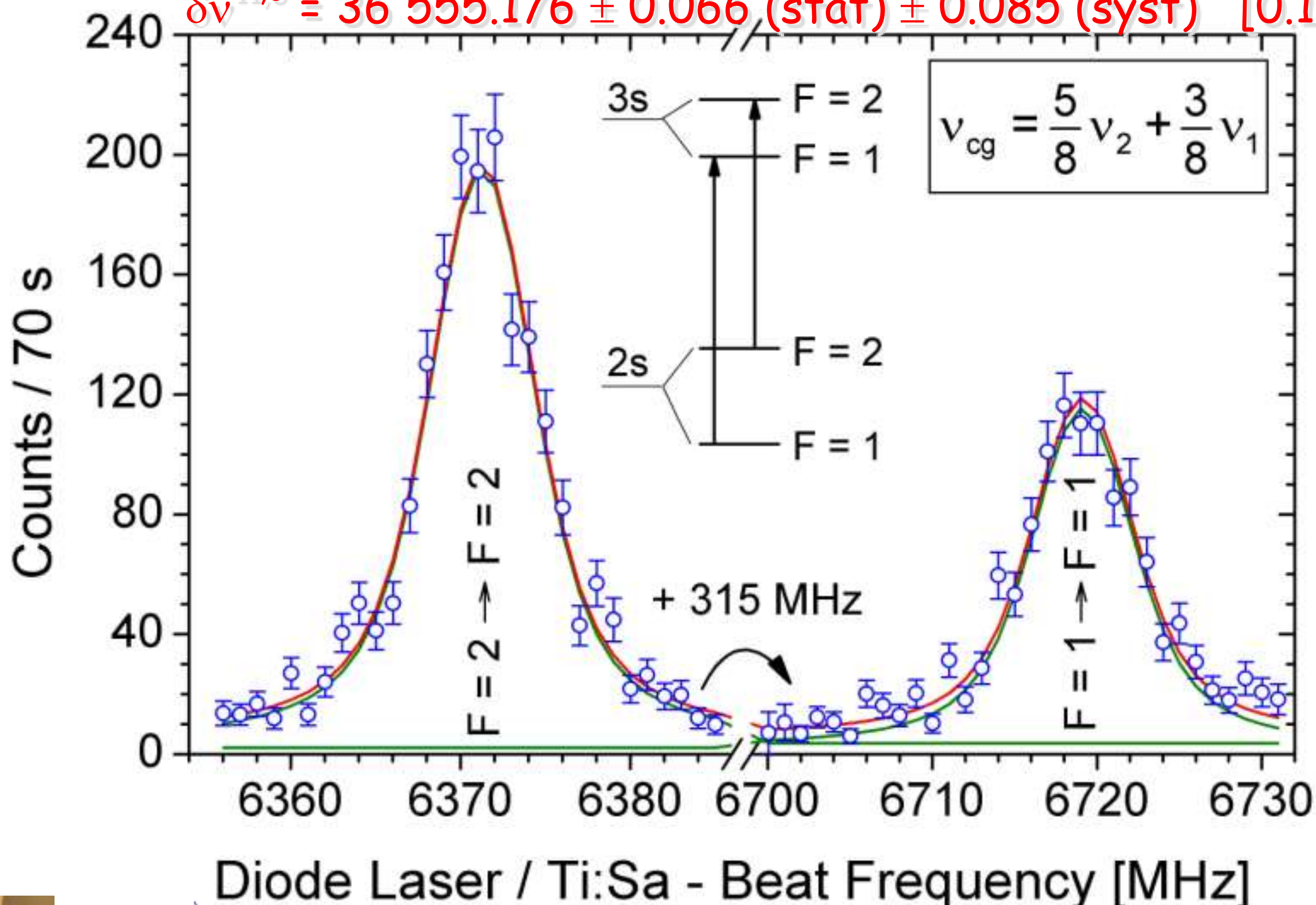


R. Sanchez et al., PRL 96, 033002 (2006)
W. Nörtershäuser et al., PRA, 83 012516 (2011)

(2) Lithium: ^{11}Li – Spectrum

Yield ≈ 30,000 ^{11}Li/s

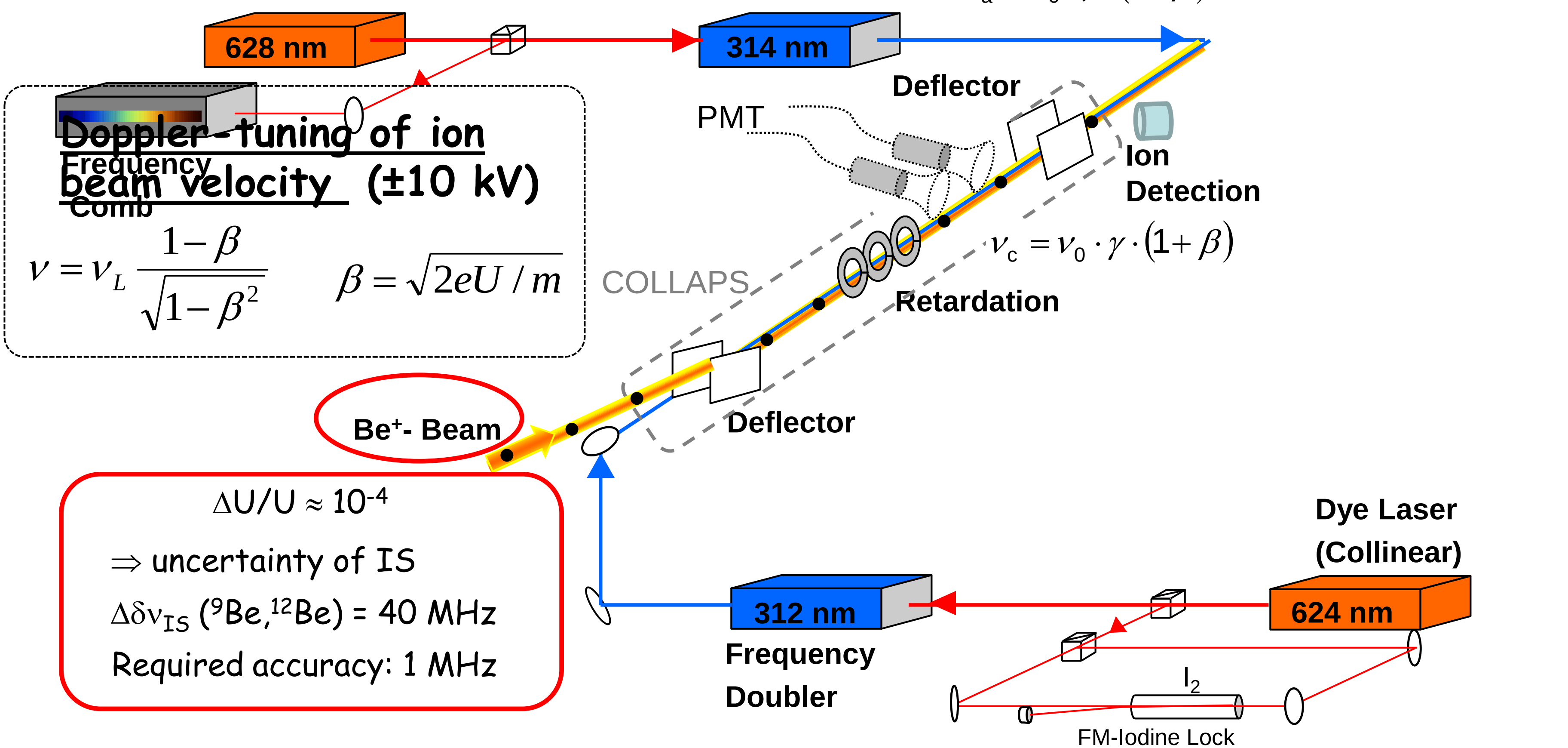
$\delta\nu^{11,6}$ = 36 555.176 ± 0.066 (stat) ± 0.085 (syst) [0.109 total]



R. Sanchez et al., PRL 96, 033002 (2006)
W. Nörtershäuser et al., PRA, 83 012516 (2011)

GSI TRIUMF ISAC

(3) Beryllium: Collinear Laser Spectroscopy



$$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$

$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

Doppler-tuning of ion beam velocity (±10 kV)

$$\nu = \nu_L \frac{1-\beta}{\sqrt{1-\beta^2}} \qquad \beta = \sqrt{2eU/m}$$

$\Delta U/U \approx 10^{-4}$

$\Rightarrow$ uncertainty of IS

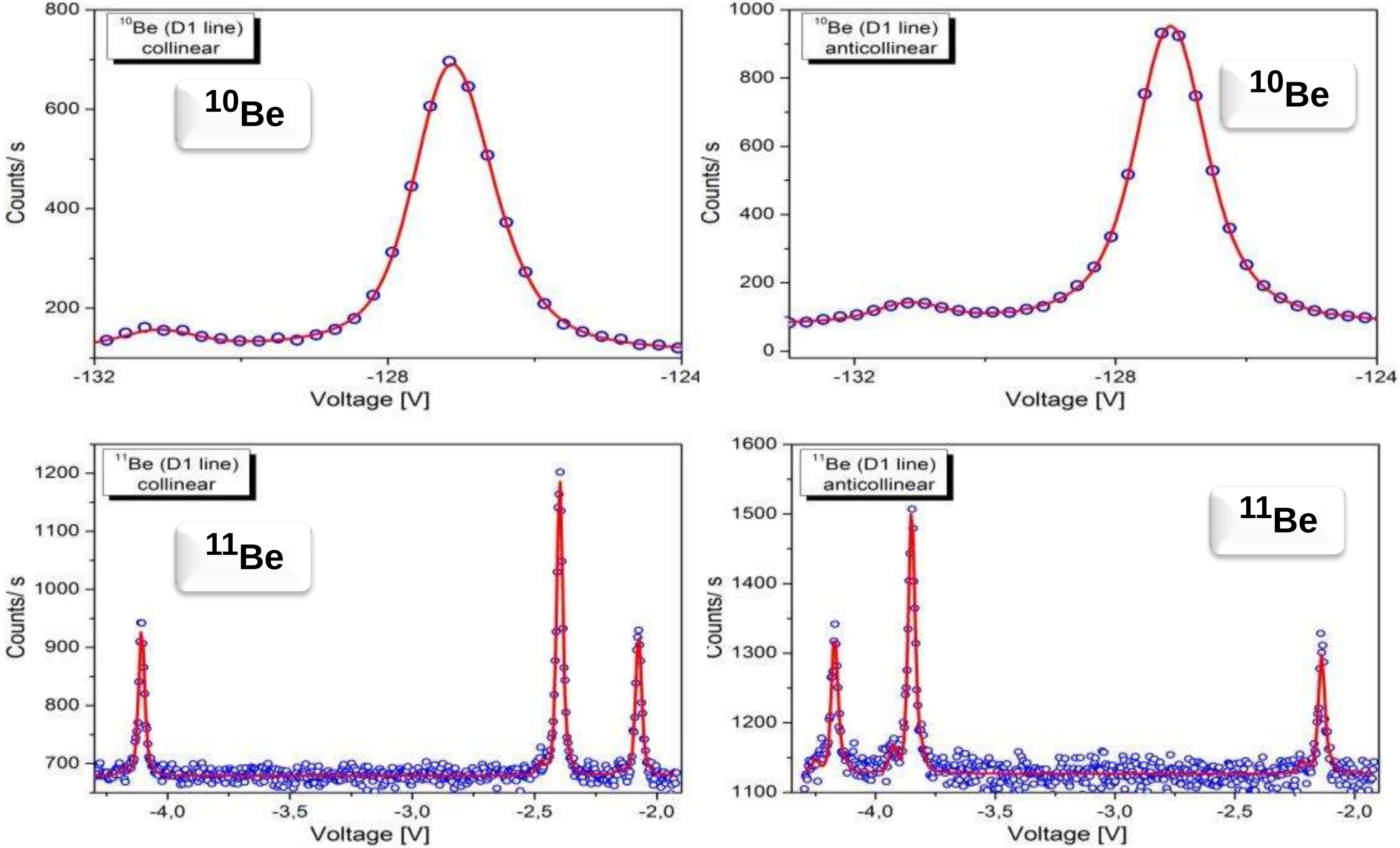
$\Delta\delta\nu_{IS}$ (^{9}Be,^{12}Be) = 40 MHz

Required accuracy: 1 MHz

Solution: Quasi-simultaneous collinear-anticollinear arrangement
Independent of uncertainties in the acceleration voltage!

$$\nu_a \cdot \nu_c = \nu_0^2 \cdot \gamma^2 \cdot (1-\beta^2) = \nu_0^2$$

(3) Beryllium: Example Spectra (2010 run)



Total Nuclear Charge Radius

$$R_c(^{A'}\mathrm{Li}) = \sqrt{R_c^2(^{A}\mathrm{Li}) + \delta \langle r_c^2 \rangle^{A,A'}}.$$

Model-independent data
in most cases not available

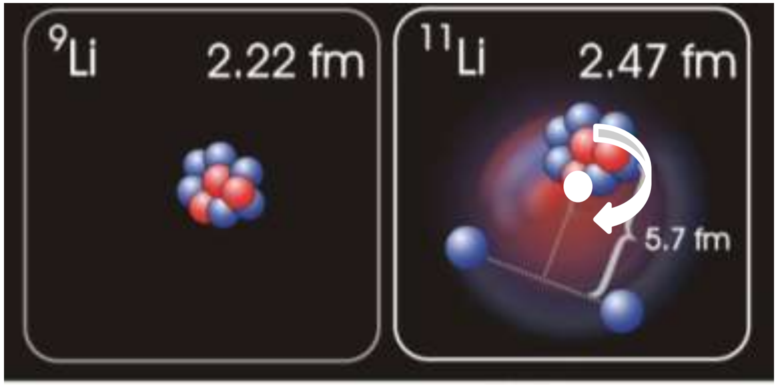
Laser Spectroscopy
Isotope Shift

Model independent !

Why bother about R_c?

- Comparison with theory
- Trend along isotones
  e.g. ^{7}Be - ^{8}B (what is the effect of the halo-proton)

Three-Body Model Interpretation



W. Nörtershäuser, P. Müller,
PhiuZ 40, 96 (2009)

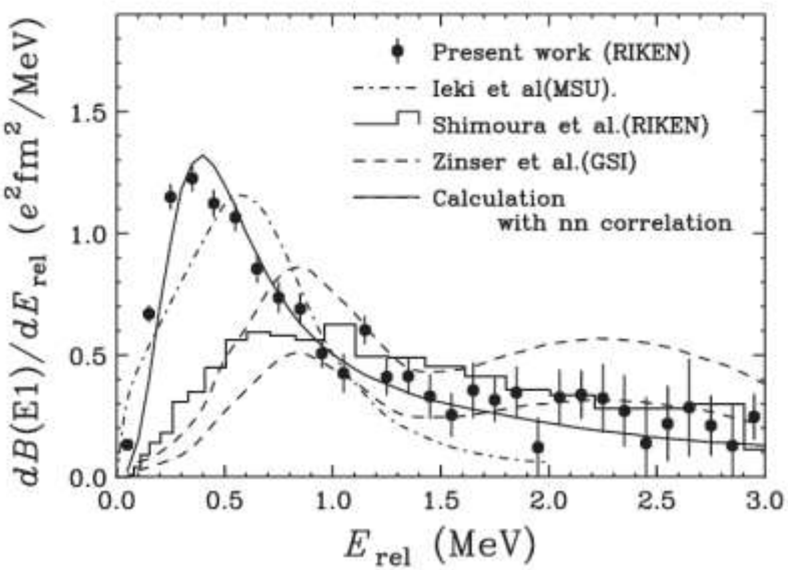
Geometrical Relation of CM-Motion:

$$\left[r_c(^{11}\mathrm{Li})\right]^2 = \left[r_c(^{9}\mathrm{Li})\right]^2 + R^2_{c-CM}$$

$$\Rightarrow R^2_{c-CM} = \left[r_c(^{11}\mathrm{Li})\right]^2 - \left[r_c(^{9}\mathrm{Li})\right]^2 = \delta\langle r^2\rangle^{9,11}$$

R_{c-2n} = 5.89(3) fm Charge Radius

Coulomb Dissociation:



$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1^2 + r_2^2 + 2\boldsymbol{r}_1 \cdot \boldsymbol{r}_2\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r^2_{c,2n}\rangle,$$

R_{c-2n} = 5.01(32) fm Coulomb Dissociation

Using the same
approach for ^{11}Be : $R_{c-n} \approx 7$ fm

Nakamura et al., PRL, 96 252502 (2006)

Uncertainties of r_c from $\delta\langle r_c \rangle$

$$\Delta E^{A,A'} = \left[\left(\frac{\mu}{M}\right)_A - \left(\frac{\mu}{M}\right)_{A'}\right]\left(E^{(1)}_{NR} + \alpha^2 E^{(1)}_{rel} + \alpha^3 E^{(1)}_{QED}\right) + \left[\left(\frac{\mu}{M}\right)_A^2 - \left(\frac{\mu}{M}\right)_{A'}^2\right] E^{(2)}_{NR} + \ldots + \Delta E^{A}_{nuc} - \Delta E^{A'}_{nuc} .$$

(1) Isotope Masses

$\Delta(\delta\nu^{7,11}) \approx 2.7$ kHz (1×10^{-7}) $\rightarrow \Delta r_c \approx \pm 0.0007$ fm

(2) Calculational Accuracy

$\Delta(\delta\nu^{7,11}) \approx 6.4$ kHz (3×10^{-7}) $\rightarrow \Delta r_c \approx \pm 0.0011$ fm

(3) Nuclear Polarizability

$\Delta(\delta\nu^{7,11}_{Pol.}) \approx 4$ kHz (2×10^{-7}) $\rightarrow \Delta r_c \approx \pm 0.0008$ fm

$\delta\nu^{7,11}_{Pol.} = 39\,(4)$ kHz (2×10^{-6}) $\rightarrow \delta r_c = 0.0047(8)$ fm

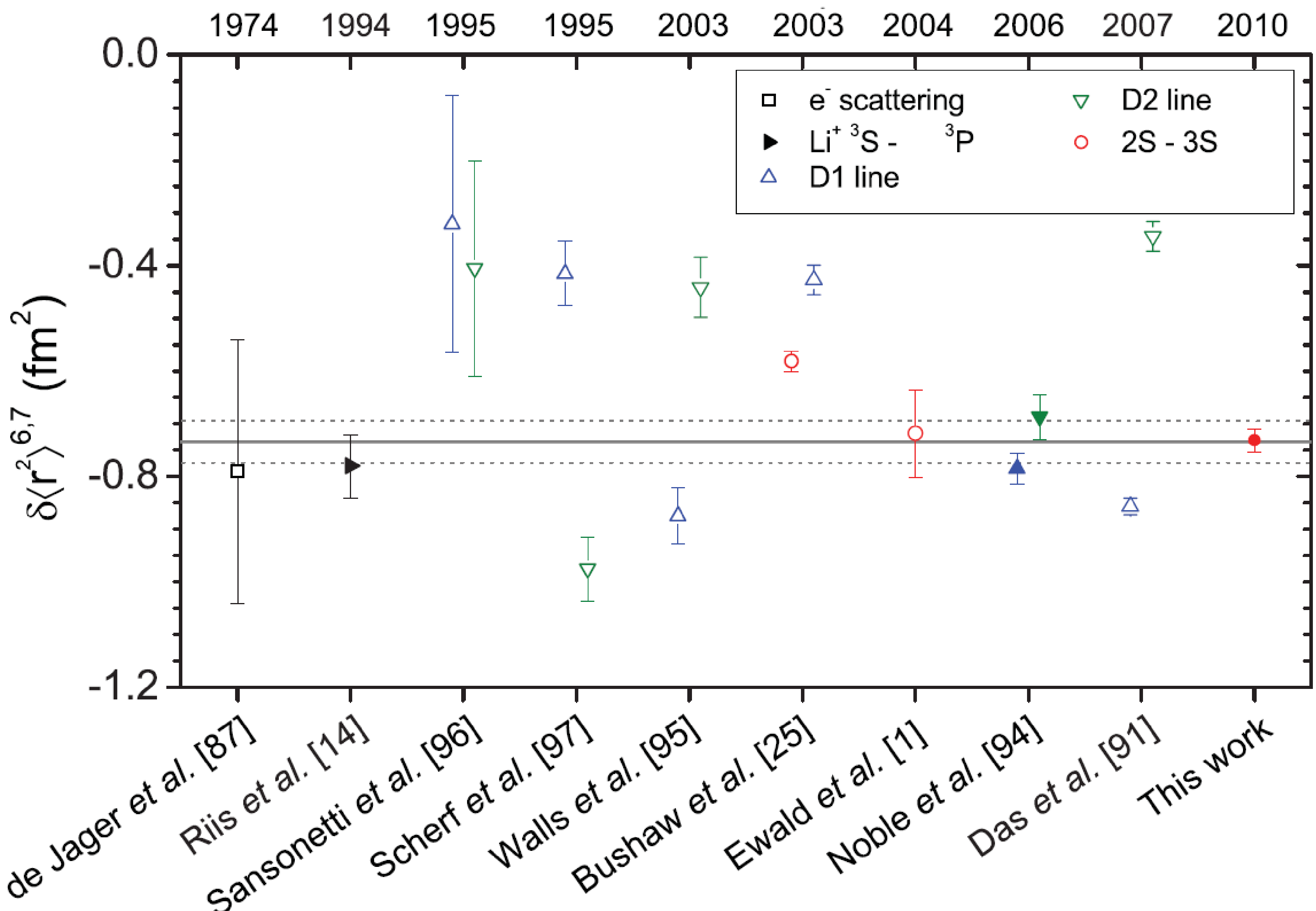
(4) Field Shift Coefficient

$\Delta C \approx 0.0017$ MHz/fm^2 (1×10^{-3}) $\rightarrow \Delta r_c \approx \pm 0.0001$ fm

(5) Experimental Uncertainty

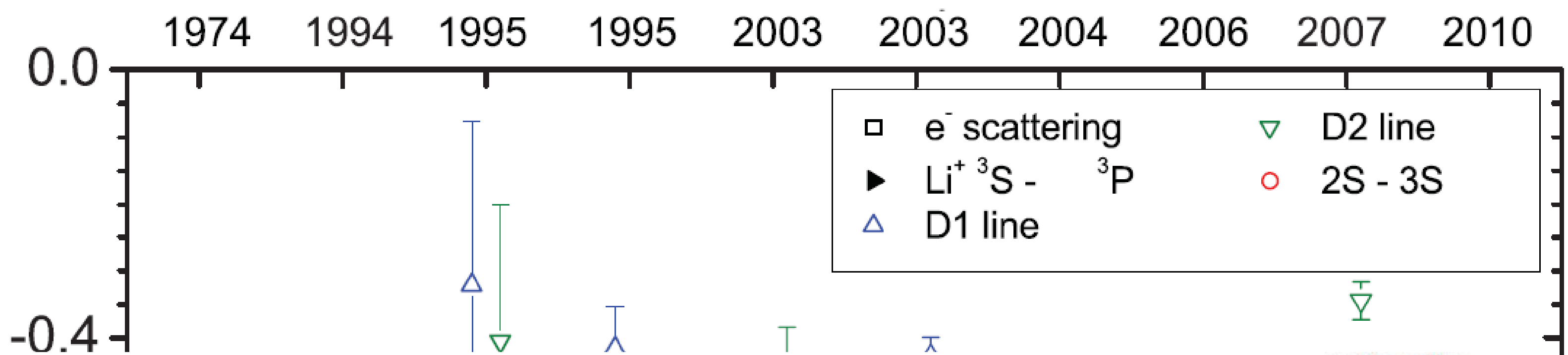
$\Delta\nu \approx 0.109$ MHz (3×10^{-6}) $\rightarrow \Delta r_c \approx \pm 0.014$ fm

^{6}Li-^{7}Li: Are Isotope Shift Calculations Only Precise or also Accurate



Nörtershäuser et al., PRA 83 012516 (2011)

^{6}Li-^{7}Li: Are Isotope Shift Calculations Only Precise or also Accurate



PRL **107,** 023001 (2011) PHYSICAL REVIEW LETTERS week ending 8 JULY 2011

Absolute Transition Frequencies and Quantum Interference in a Frequency Comb Based Measurement of the ^{6,7}Li *D* Lines

Craig J. Sansonetti,[1] C. E. Simien,[1,*] J. D. Gillaspy,[1] Joseph N. Tan,[1] Samuel M. Brewer,[2,1] Roger C. Brown,[2,1] Saijun Wu,[1] and J. V. Porto[1]

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(Received 14 March 2011; published 6 July 2011)

Optical frequencies of the *D* lines of ^{6,7}Li were measured with a relative accuracy of 5×10^{-11} using an optical comb synthesizer. Quantum interference in the laser induced fluorescence for the partially resolved *D*2 lines was found to produce polarization dependent shifts as large as 1 MHz. Our results resolve large discrepancies among previous experiments and between all experiments and theory. The fine-structure splittings for ^{6}Li and ^{7}Li are 10052.837(22) MHz and 10053.435(21) MHz. The splitting isotope shift is 0.599(30) MHz, in reasonable agreement with recent theoretical calculations.

DOI: 10.1103/PhysRevLett.107.023001 PACS numbers: 32.10.Fn, 32.30.Jc, 42.50.Gy, 42.62.Eh

Nörtershäuser et al., PRA 83 012516 (2011)

Absolute Nuclear Charge Radii

$$R_c(^{A'}\mathrm{Li}) = \sqrt{R_c^2(^{A}\mathrm{Li}) + \delta \langle r_c^2 \rangle^{A,A'}}.$$

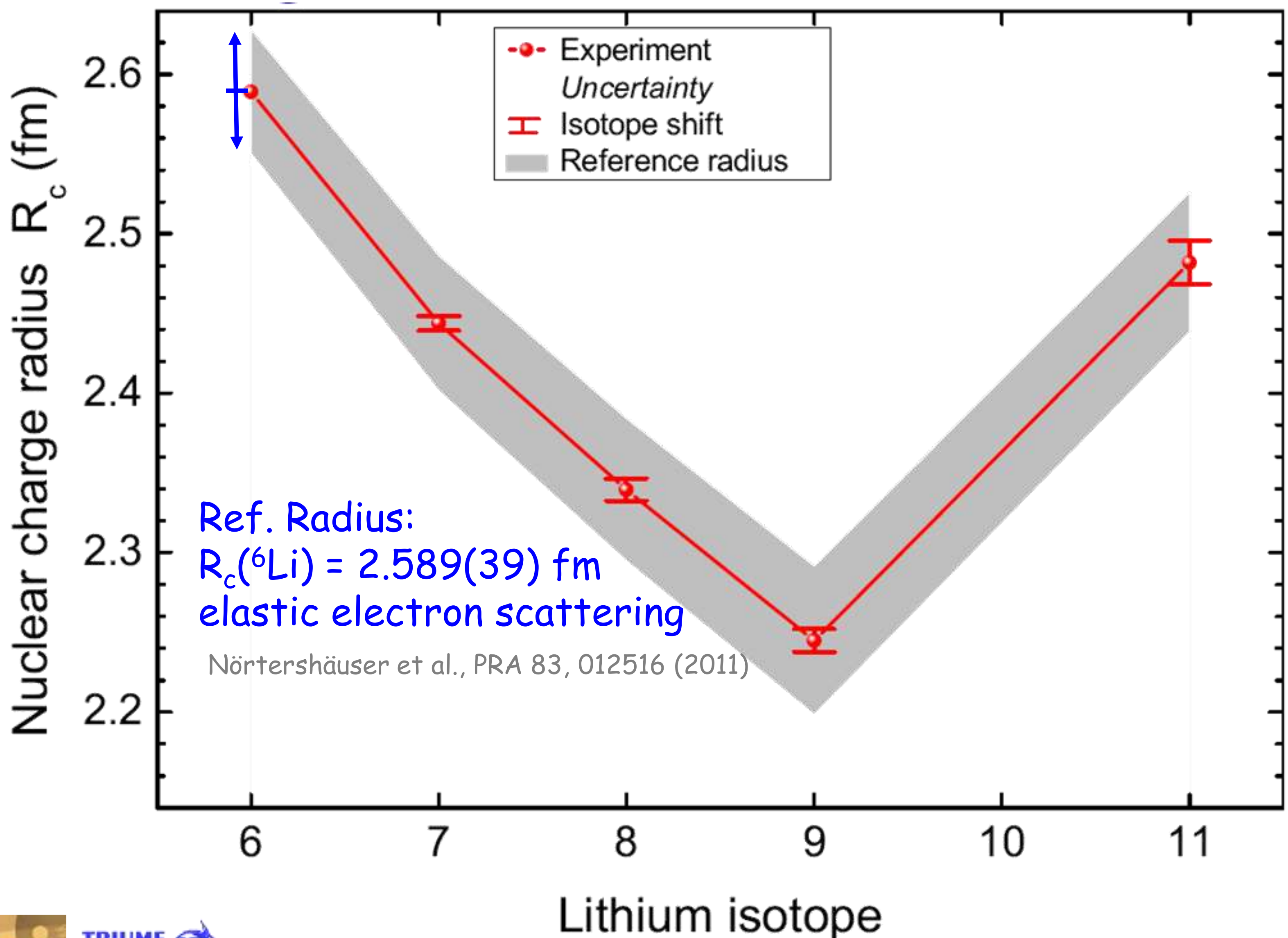
Laser Spectroscopy
Isotope Shift

Model independent !

Elastic Electron Scattering
^{4}He: 1.681 (4) fm,
^{6}Li: 2.589 (39) fm
^{9}Be: 2.519 (12) fm

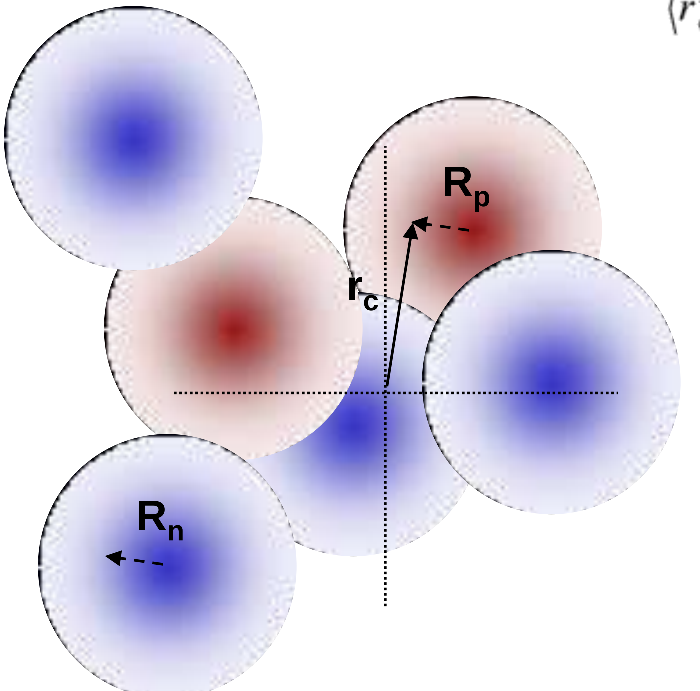
Muonic Atoms (X-Ray)
Laser Spectroscopy: Muonic Atoms
H-Like Systems

Charge Radii of Lithium Isotopes



Nörtershäuser et al., PRC 84 024307 (2011)

Calculating rms Charge Radii from Point-Proton Radii



$$\langle r_c^2 \rangle = \langle r_{pp}^2 \rangle + R_p^2 + \frac{N}{Z} R_n^2 + \frac{3\hbar^2}{4{M_p}^2 c^2} + \langle r_c^2 \rangle_{so} + MEC$$

Spin-Orbit Contribution for He:
G. Papadimitriou, *et al.* PRC **84**, 051304(R) (2011)
$\langle r_c^2 \rangle_{SO}$ = -0.0718 / -0.158 fm^2

R_p^2 = 0.766(12) fm^2
R_n^2 = -0.120(5) fm^2

Li isotopes , PRC 84 024307 (2011):

Isotope	Model	$\langle r_c^2 \rangle_{so}^p$ (fm^2)	$\langle r_c^2 \rangle_{so}^n$ (fm^2)
^{6}Li	FMD	+0.006	−0.006
^{7}Li	FMD	+0.012	−0.020
^{8}Li	FMD	+0.011	−0.056
^{9}Li	FMD	+0.021	−0.084
^{9}Li	FMD (VAP)	+0.023	−0.089
^{11}Li − $(p_{1/2})^2$	FMD (VAP)	+0.024	−0.003
^{11}Li − $(s_{1/2})^2$	FMD (VAP)	+0.023	−0.088
^{9}Li (free)	TOSM[a]	+0.026	−0.091
^{9}Li in ^{11}Li	TOSM[b]	+0.026	−0.097
2n halo in ^{11}Li	TOSM[c]		+0.052
^{11}Li	TOSM[d]	+0.026	−0.045
2n halo in ^{11}Li	3BM[e]		+0.048

Charge Radius Contributions

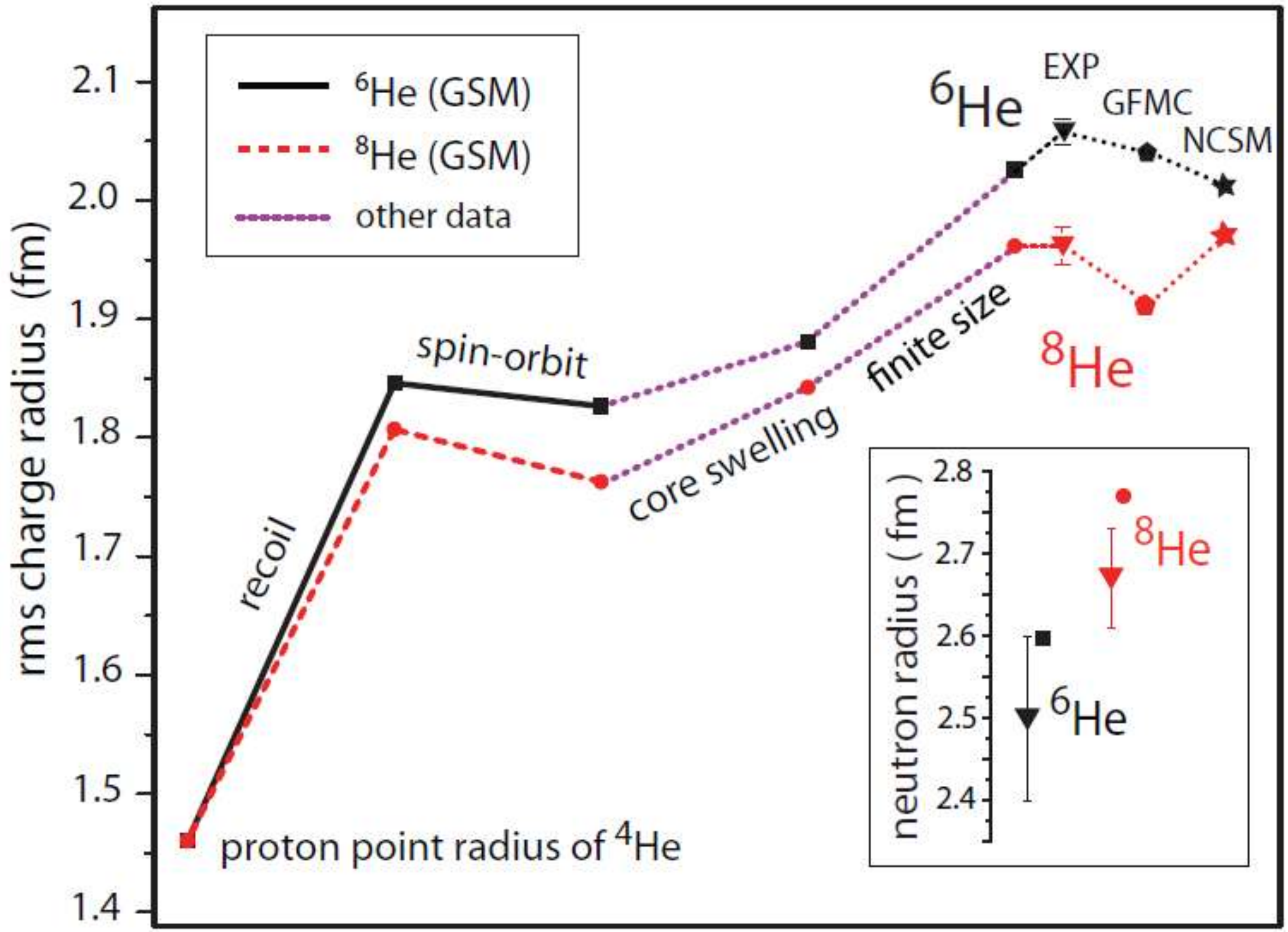
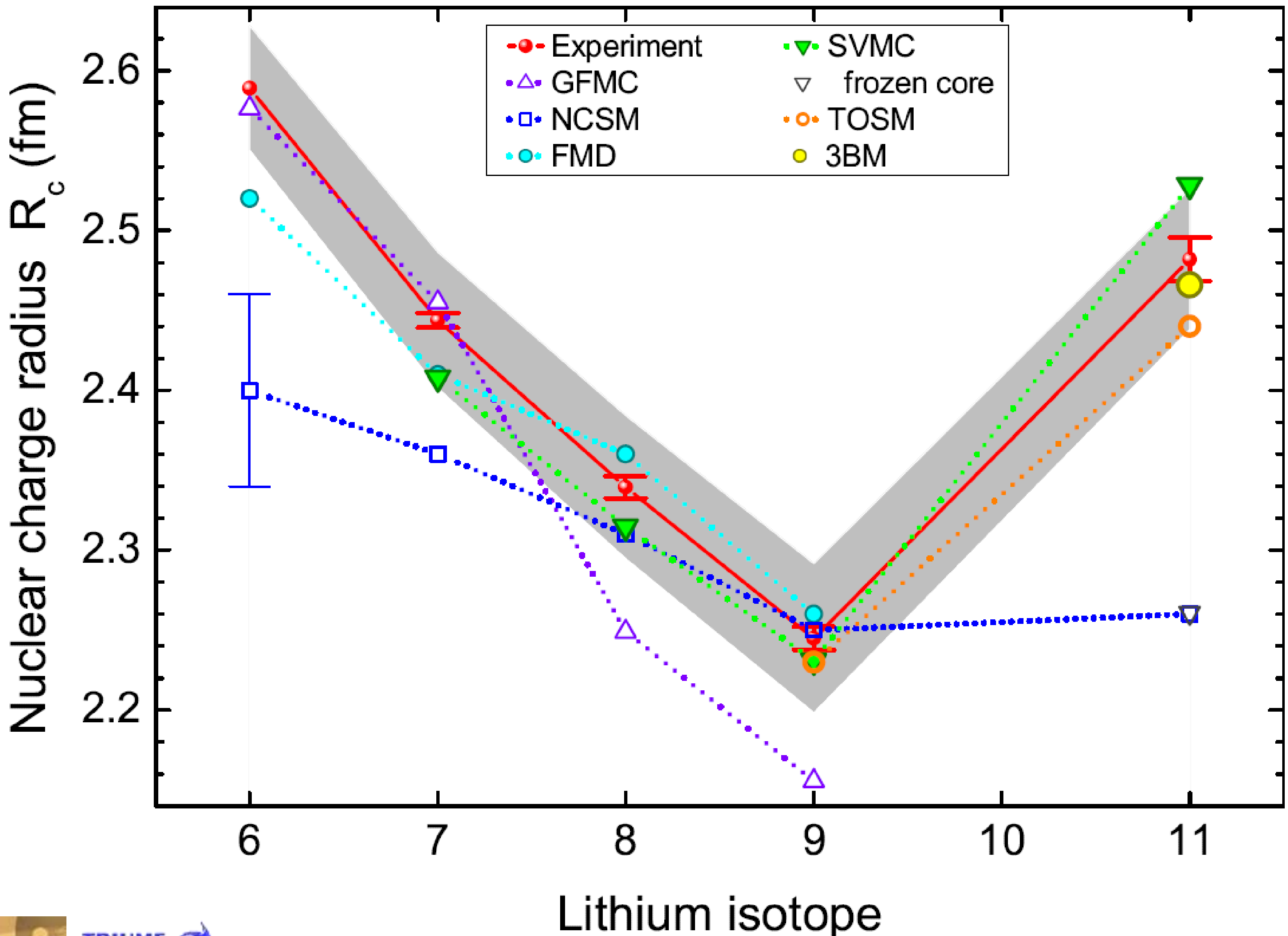


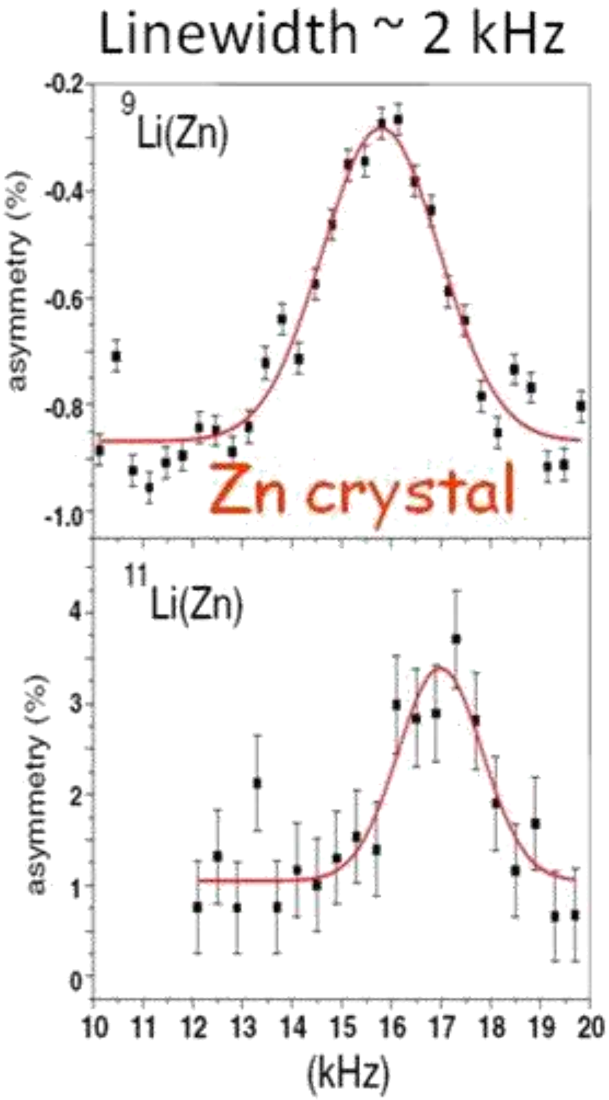
Fig. 4 from G. Papadimitriou, *et al.* PRC **84**, 051304(R) (2011)
(core swelling from GFMC)

Charge Radii of Lithium Isotopes

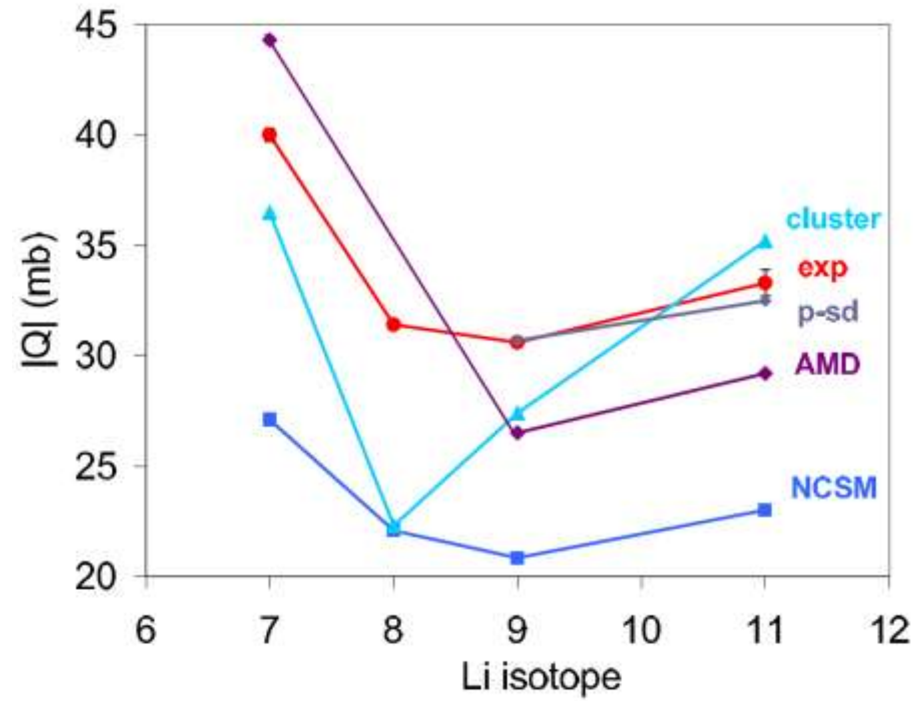


Nörtershäuser et al., PRC 84 024307 (2011)

The Quadrupole Moment of ^{11}Li



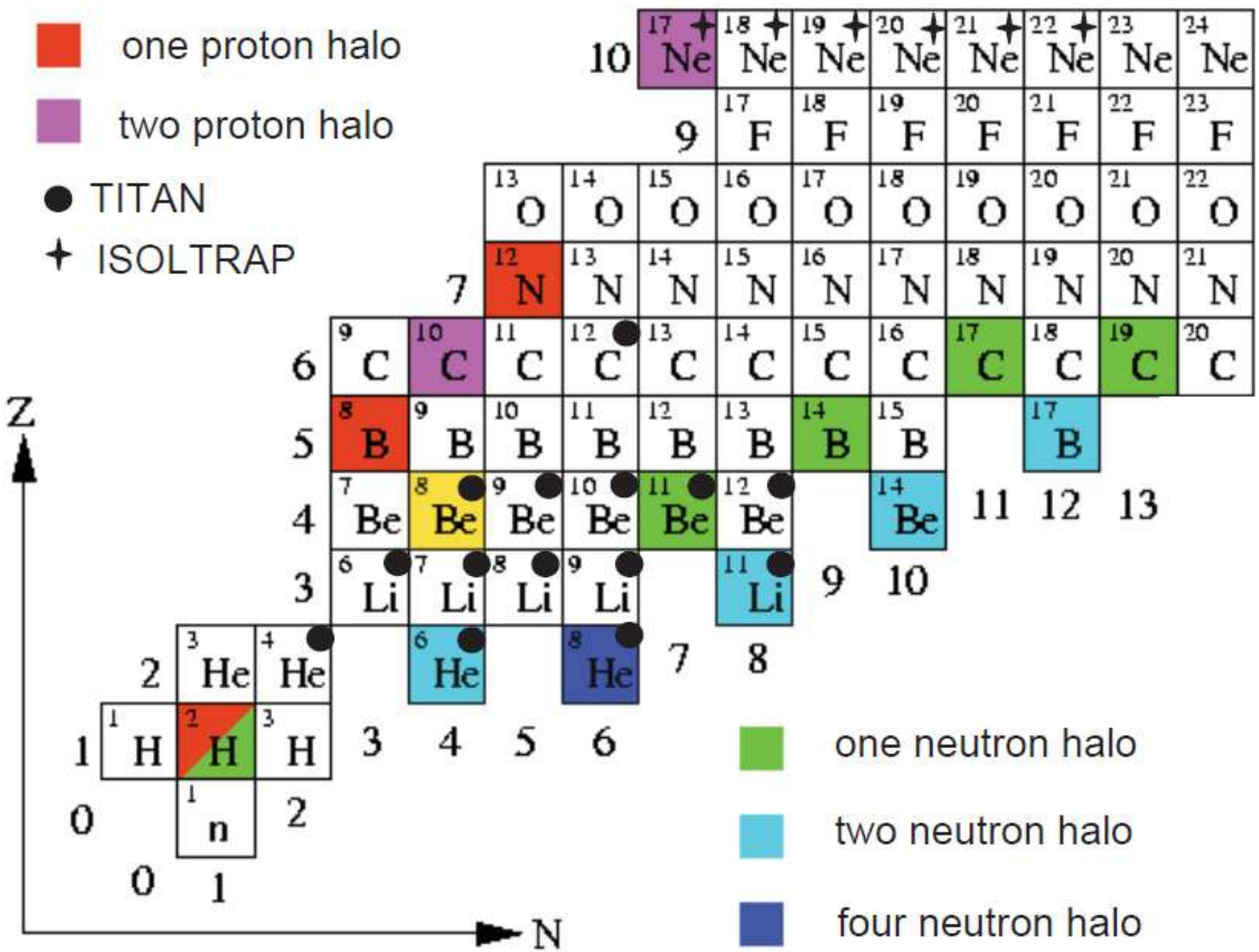
$Q(^{11}Li)/Q(^{9}Li) = 1.088(15)$



All approaches predict an increase of Q from ^{9}Li to ^{11}Li:
Effect of larger R_C or
or
(quadrupole) core polarization

R. Neugart et al., PRL 101, 132502 (2008)

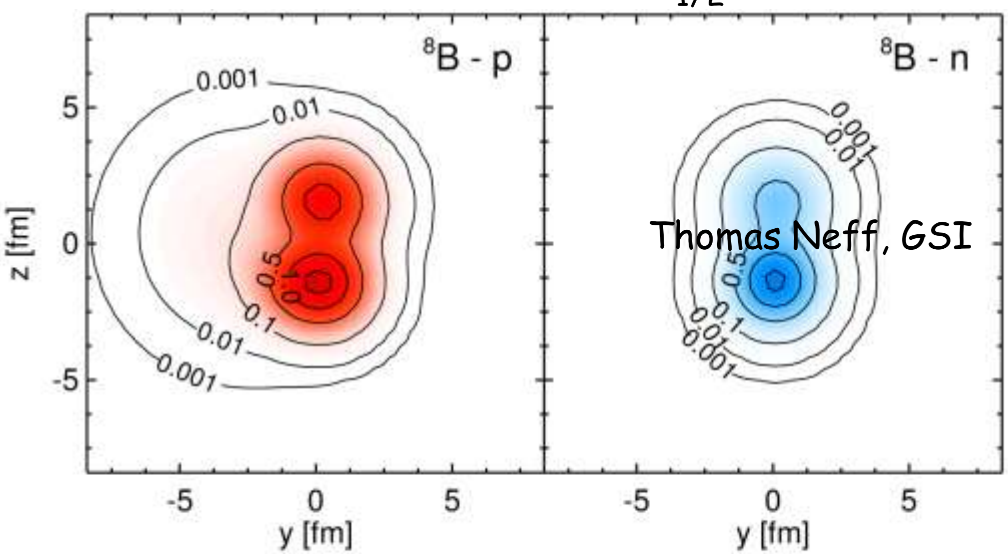
The Realm of Halo Nuclei



Next Light Element: Boron (Z=4)

^{8}B is the best proton-halo candidate !

$^{8}B = {}^{7}Li + p$ $\quad T_{1/2} \approx 800$ ms



BUT …

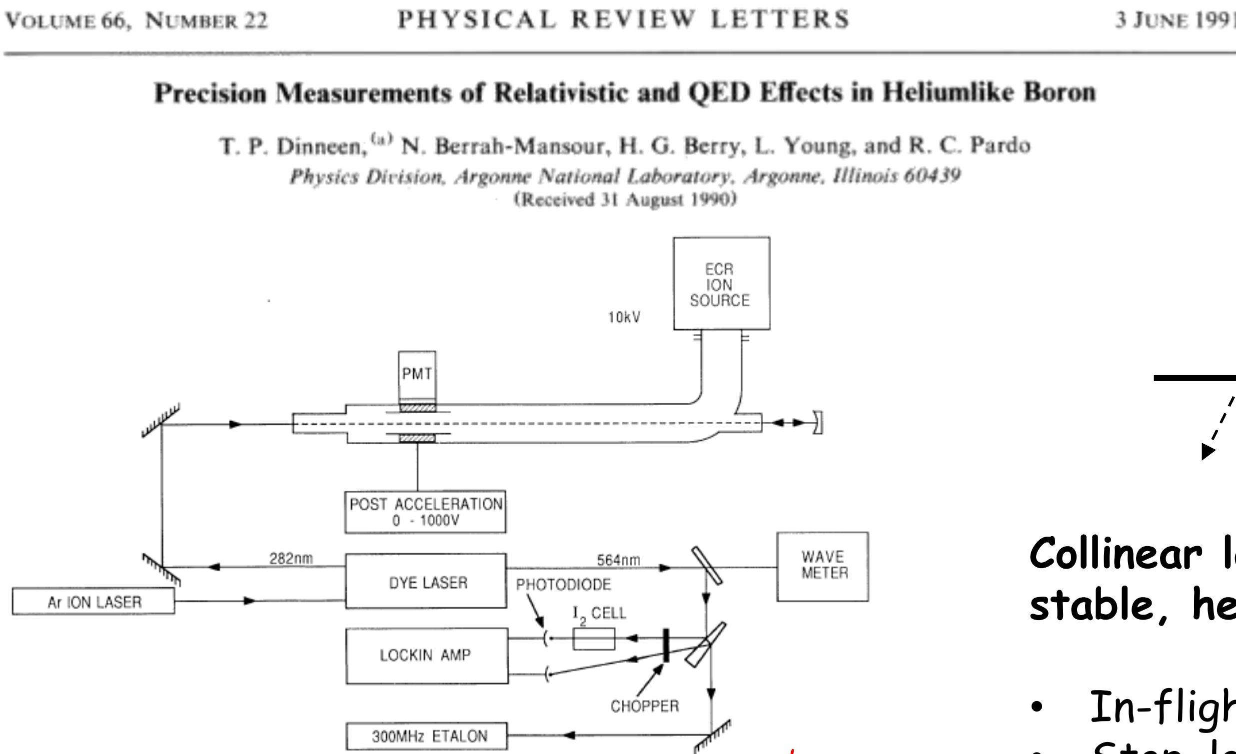
Mass shift calculations only available for B^{2+} or higher charge states

Laser-accessible transition: He-like B^{3+}

Starting from metastable state τ (1s2s $^{3}S_{1}$) ~ 150 ms

In-flight production required

Approach for Boron

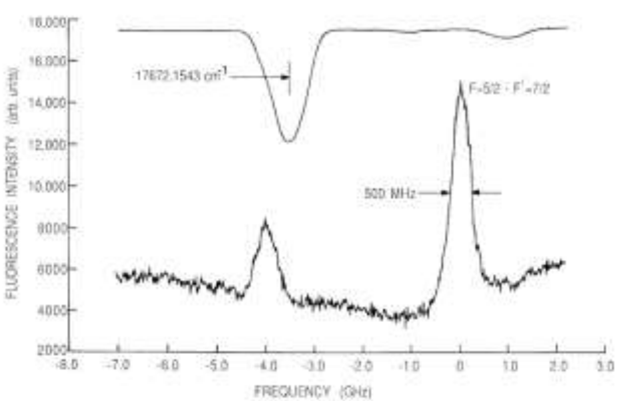

VOLUME 66, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 1991

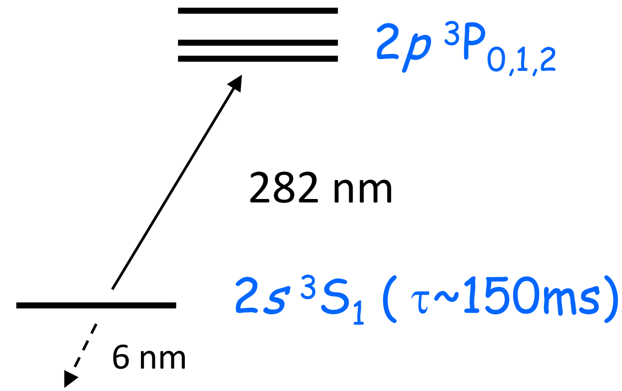
Precision Measurements of Relativistic and QED Effects in Heliumlike Boron

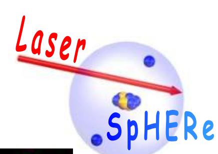
T. P. Dinneen,[a] N. Berrah-Mansour, H. G. Berry, L. Young, and R. C. Pardo

Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 31 August 1990)







Ch. Geppert
A. Krieger
Z.-T. Lu
P. Müller
W. Nörtershäuser

Collinear laser spectroscopy of meta-stable, helium-like B^{3+} from an ECR

- In-flight production at ATLAS
- Stop, low energy B^{+} -> source
  … gas catcher + ECR
- Charge breeding
  … to B^{3+} or B^{4+}
- Populate metastable state
  … in source or charge-ex.
- High-resolution laser excitation
  … coll.-anticoll., Λ-Spectroscopy

Conclusion

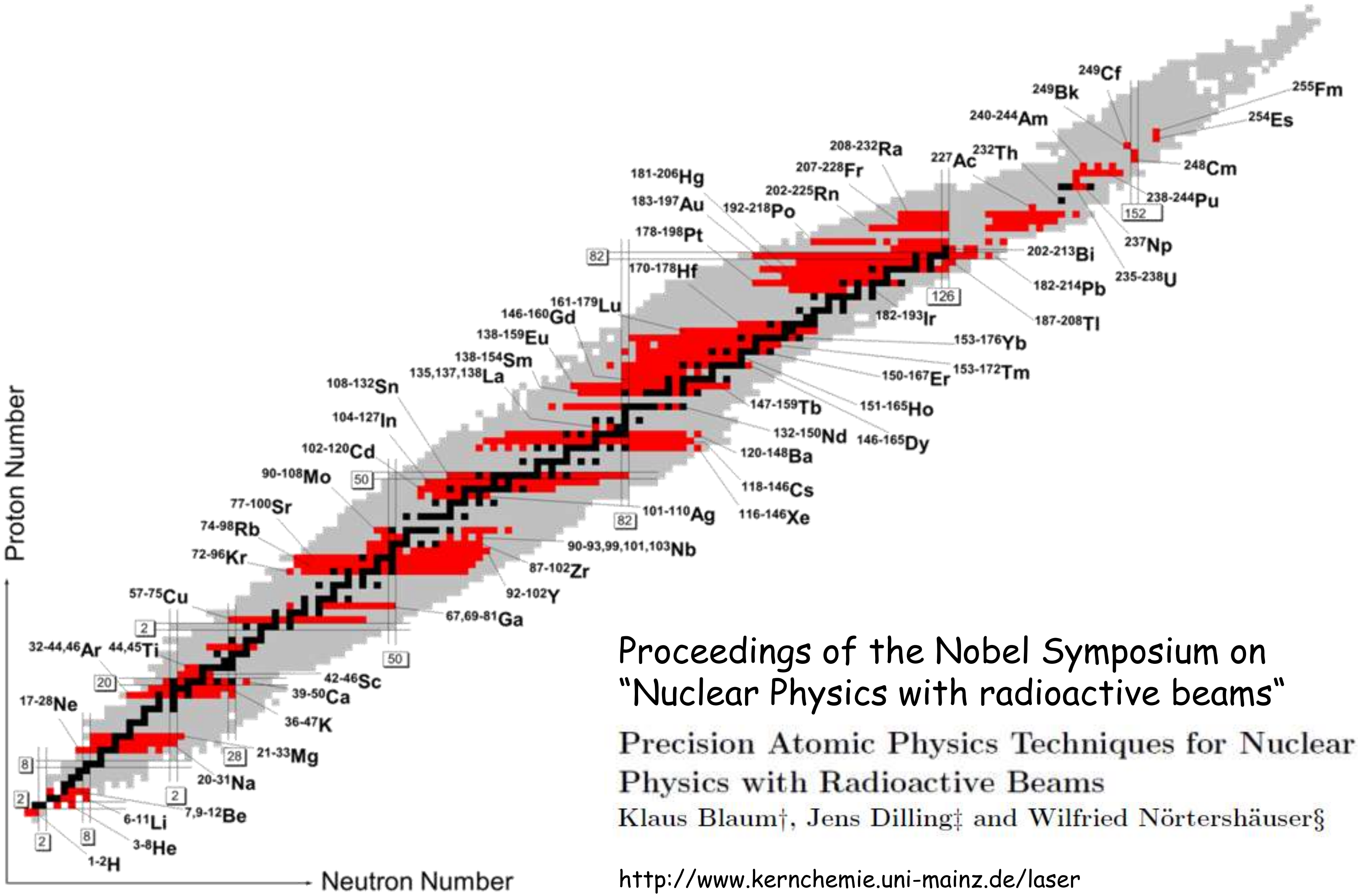
- Laser Spectroscopy of short-lived light isotopes provides accurate data of nuclear ground-state properties
- Results along isotopic chains are benchmarks for nuclear structure models
- For neutron-halo nuclei, changes in nuclear charge radii are dominated by recoil effects
- Unambiguous proof for a proton halo is still missing → Spectroscopy on ^{8}B required

The field has seen tremendous progress in atomic theory

… but further improvements are required !

- Specific mass shift constants, field shift constants, and hyperfine fields for more complicated systems with good accuracy
- Absolute nuclear charge radii from transition frequencies

Laser Spectroscopy of Short-Lived Isotopes



Proceedings of the Nobel Symposium on "Nuclear Physics with radioactive beams"

Precision Atomic Physics Techniques for Nuclear Physics with Radioactive Beams

Klaus Blaum†, Jens Dilling‡ and Wilfried Nörtershäuser§

http://www.kernchemie.uni-mainz.de/laser

Thank you

in the front (from the left): Juliane Weber, **Christian Gorges**, **Nadja Frömmgen**, **Christopher Geppert**, **Stefan Schmidt**, **Michael Hammen**

in the back (from the left): **Elisa Will**, **Benjamin Botermann**, **Andreas Krieger**, **Wilfried Nörtershäuser**, **Rodolfo Sanchez**

Laser SpHERe

HELMHOLTZ GEMEINSCHAFT

Bundesministerium für Bildung und Forschung

EURONS

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