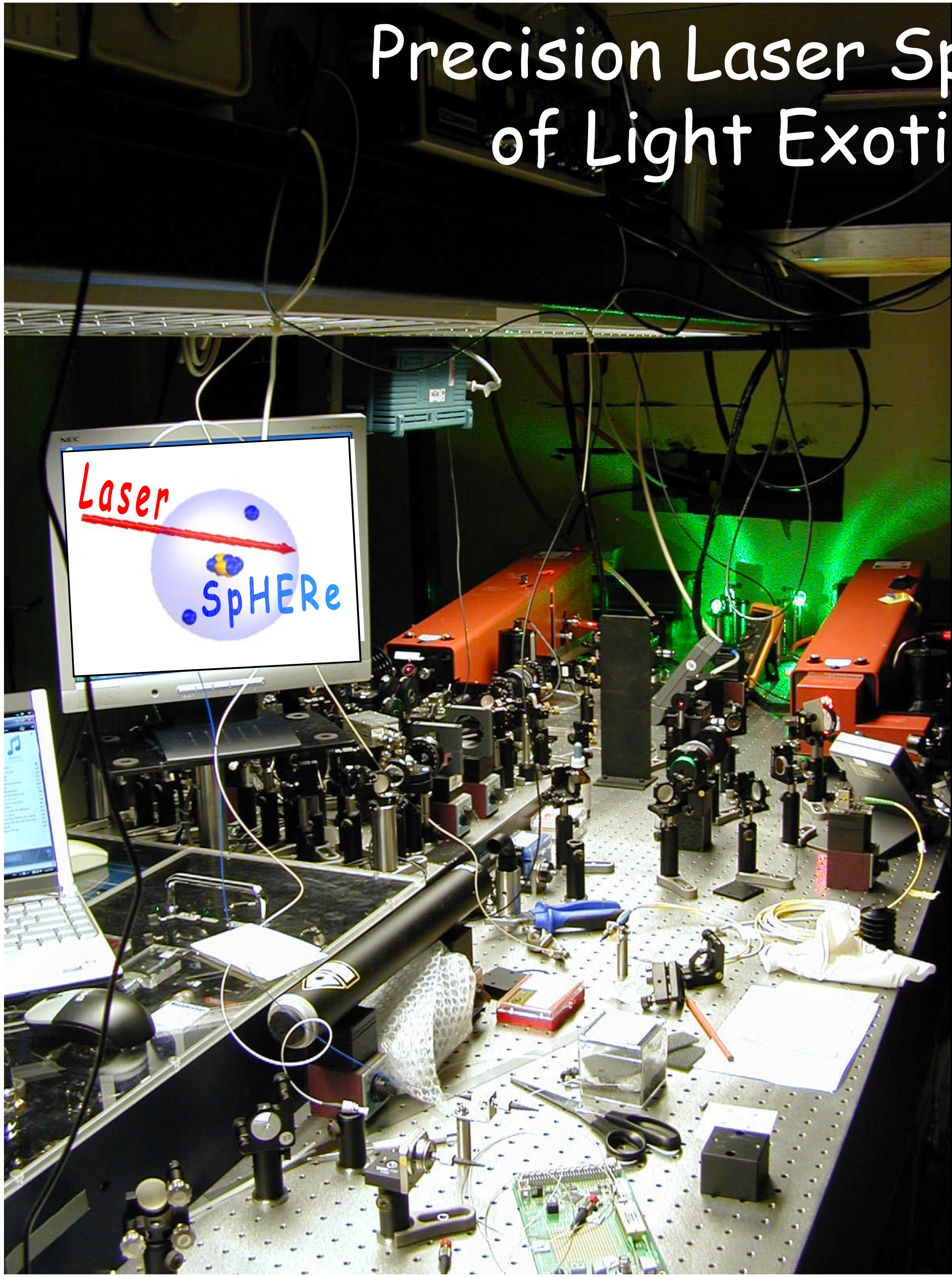
Precision Laser Spectroscopy of Light Exotic Nuclei



W. Nörtershäuser

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GSI Helmholtzzentrum für Schwerionenforschung

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

Outline

- Introduction and Motivation
- General Approach
- Lithium
  - Resonance Ionization Mass Spectroscopy
  - Charge Radii - Results and Interpretation
  - Absolute Charge Radii from Optical Measurements ?
- Helium
  - Single-Atom Spectroscopy in a Magneto-Optical Trap
- Beryllium
  - Frequency-Comb Based Collinear Laser Spectroscopy
  - Nuclear Charge Radii
- Open Questions and Outlook

Optical Spectroscopy in the Nuclear Chart
Principle

Hyperfine Structure:

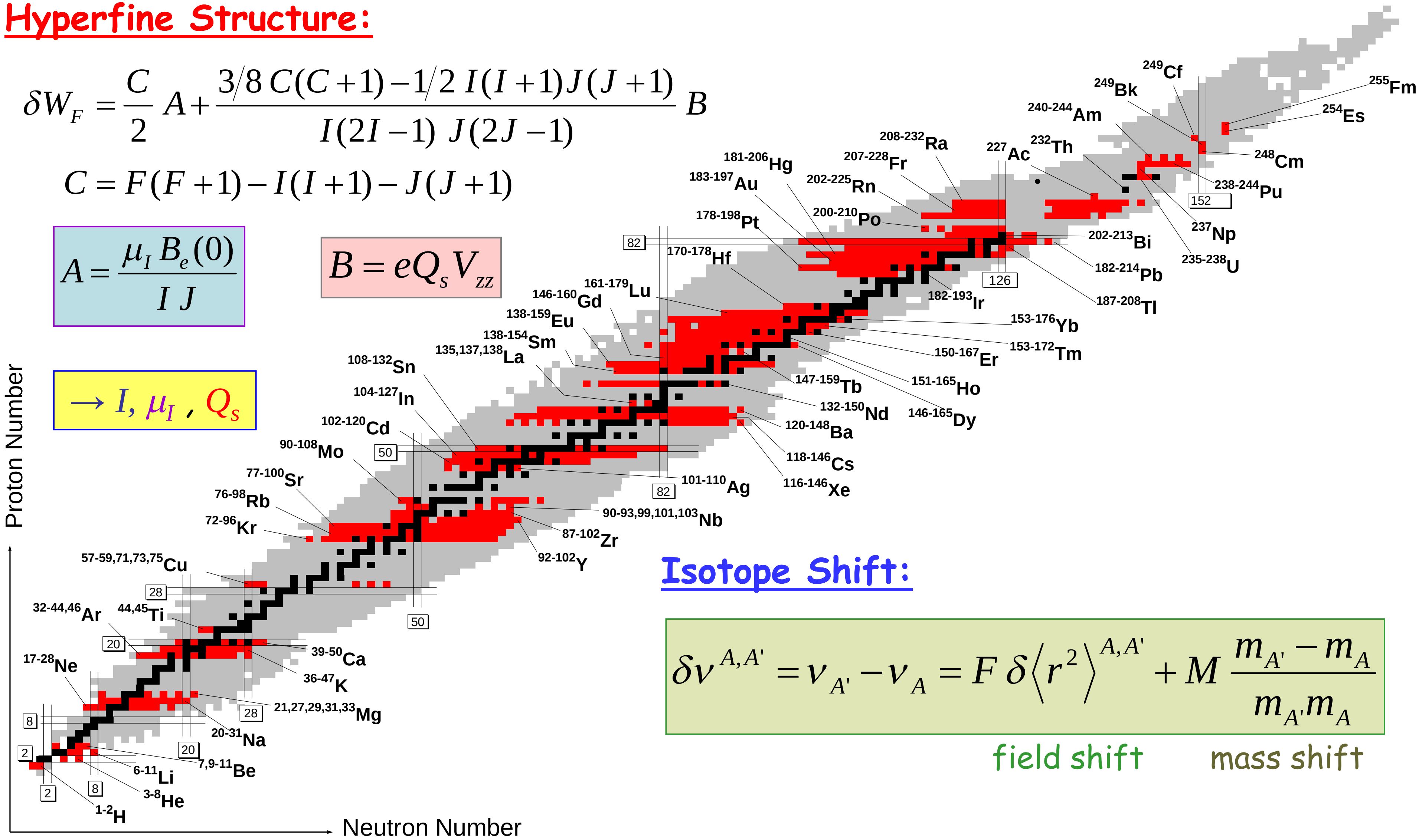
$$\delta W_F = \frac{C}{2} A + \frac{3/8\, C(C+1) - 1/2\, I(I+1) J(J+1)}{I(2I-1)\; J(2J-1)} B$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

$$A = \frac{\mu_I B_e(0)}{I\,J}$$

$$B = eQ_s V_{zz}$$

$$\rightarrow I,\ \mu_I\ ,\ Q_s$$



Isotope Shift:

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

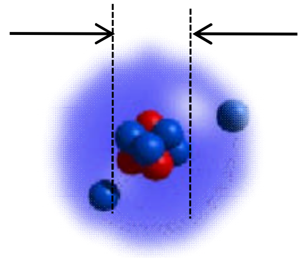
field shift   mass shift

H.-J. Kluge and W. Nörtershäuser, Spectrochim. Acta B, 58 (2003)
http://www.gsi.de/forschung/ap/projects/laser/survey.html

Motivation

(a) Exotic Structure of Halo Nuclei

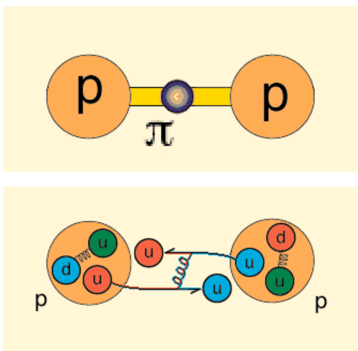
Model-Independent Approach
to the Core Size in Halo Nuclei

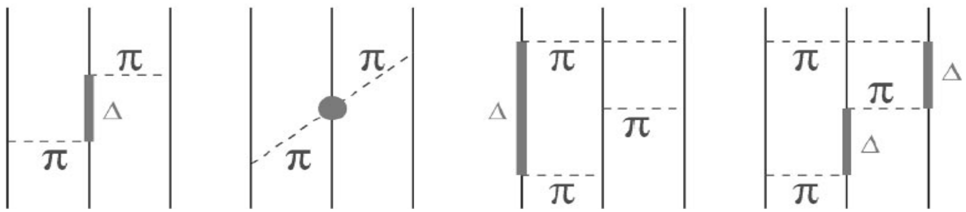


(b) Validating ab-initio Nuclear Structure Calculations

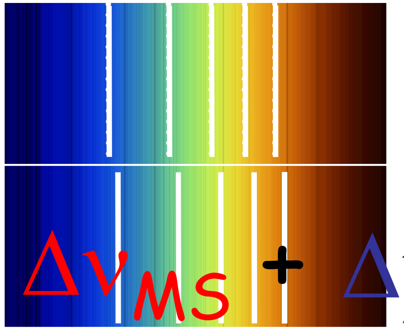
Benchmarks for Nuclear Structure Calculations based on Nucleon-Nucleon and Three-Nucleon Potentials

(Greens-Function Monte Carlo, No-Core Shell Modell, Fermionic Molecular Dynamics)





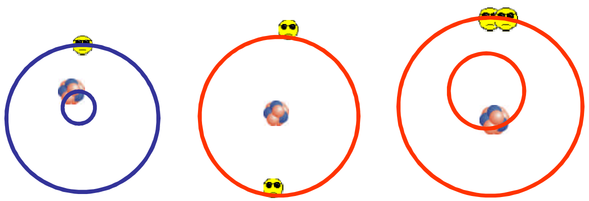
Isotope Shift

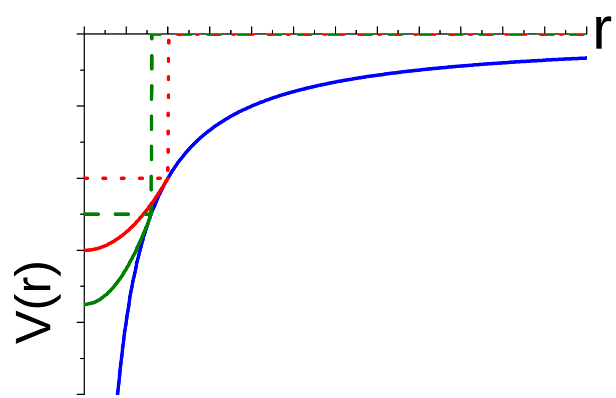


= Frequency difference in an electronic transition between two isotopes

$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS}$$

$$\frac{2\pi Z}{3}\,\Delta|\psi(0)|^2\,\delta\langle r^2\rangle$$





Charge Radii from Isotope Shifts

$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

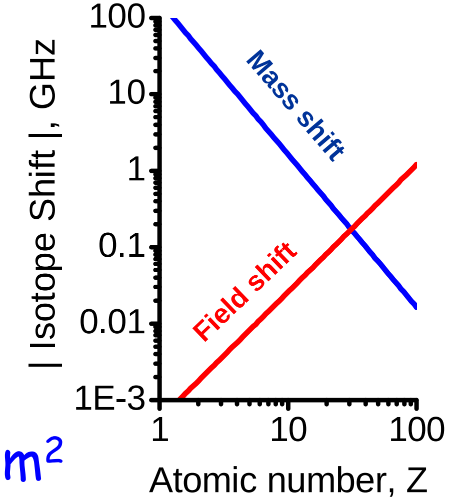
$$\delta\nu_{FS} = \frac{2\pi}{3} \Delta|\psi(0)|^2 \, \delta\langle r^2 \rangle$$

EXPERIMENT

THEORY

$C(Li) \approx 1.6$ MHz/fm^2

^6Li-^{11}Li : ≈36 GHz



Charge Radius :

$$\delta\langle r^2 \rangle^{A,A'} = \frac{\delta\nu^{A,A'}_{measured} - \delta\nu^{A,A'}_{MS,\,Theory}}{C}$$

$$\langle r_c^2 \rangle_A = \langle r_c^2 \rangle_7 + \frac{\delta\nu^{A,7} - \delta\nu^{A,7}_{MS}}{-1.5661\ \mathrm{MHz/fm^2}} .$$

Theoretically required:
Accuracy of ~ 100 kHz
Field Shift Factor

Experimentally required:
Accuracy of ~ 100 kHz
High sensitivity : $\varepsilon > 10^{-4}$
Fast technique: $T_{1/2}$ ~ s - ms

Development of Mass Shift Calculations

Isotope	[Yan 03]	[Puch06]	[Yan 08]	[Puch08]
^{6}Li	11 453.010 (56)	- 11 452.822 (2) (0)	-11 452.821 (2)	-11 452.8205 (23)(2)
^{8}Li	8 635.113 (42)	8 634.990 (1) (1)	8 634.980 (2)	8 634.9812 (17)(9)
^{9}Li	15 332.025 (75)	15 331.797 (3)(13)	15 331.799 (3)	15 331.7995 (31)(12)
^{11}Li	25 101.812 (123)	25 101.473 (9)(21)	25 101.470 (5)	25 101.5028 (64)(27)

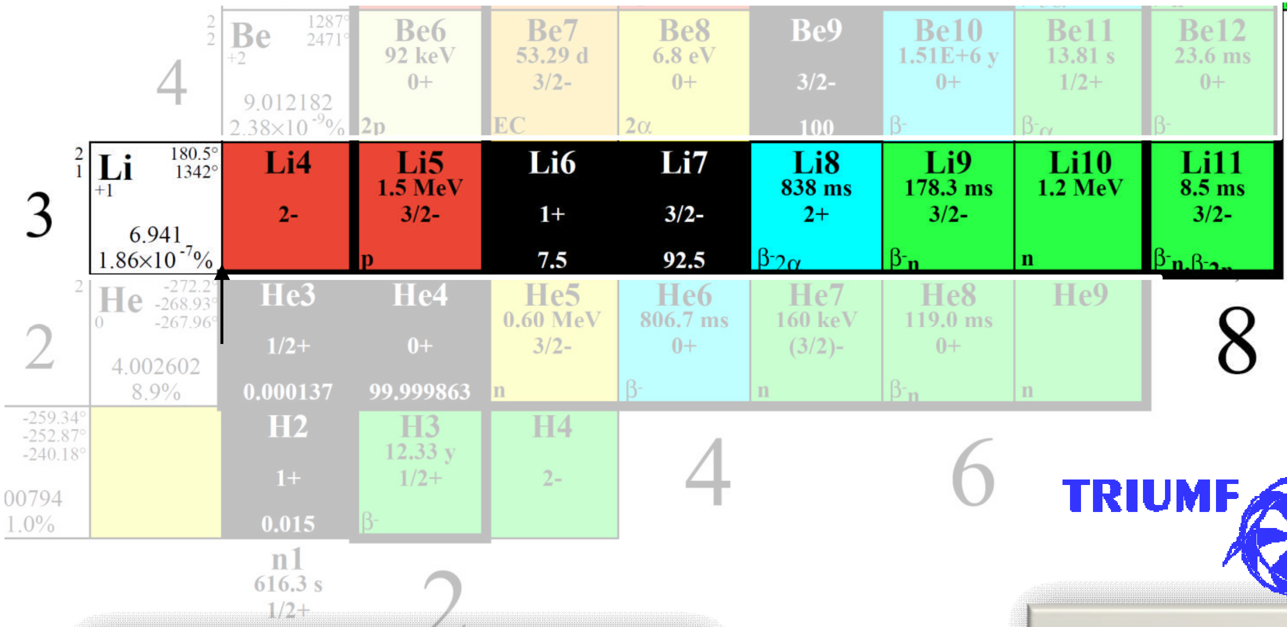
$$C = \frac{2\pi}{3} Z\alpha^4 \left\langle \sum_a \delta^{(3)}(r_a) \right\rangle [1 - (Z\alpha)^2 \ln(Z\alpha m r_{ch})]$$

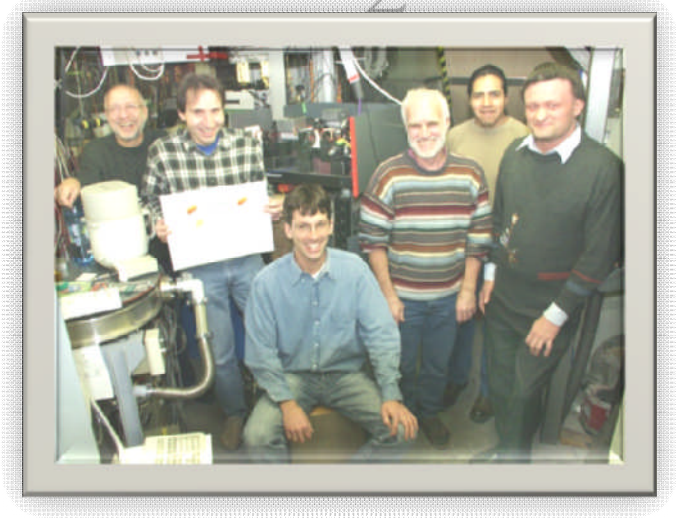
Isotope	[Puch08]
^{6}Li	−1.5719 (16)
^{8}Li	−1.5720 (16)
^{9}Li	−1.5721 (16)
^{11}Li	−1.5768 (17)

Year	M(^{11}Li) amu	$\Delta(\delta\nu^{6,11})$ kHz	Ref
2000	11.043 796 (29)	0	AME2003
2006	11.043 715 7 (54)	-329	MISTRAL
2008	11.043 723 61 (69)	-295	TITAN

Case 1: Lithium

Laser SpHERe



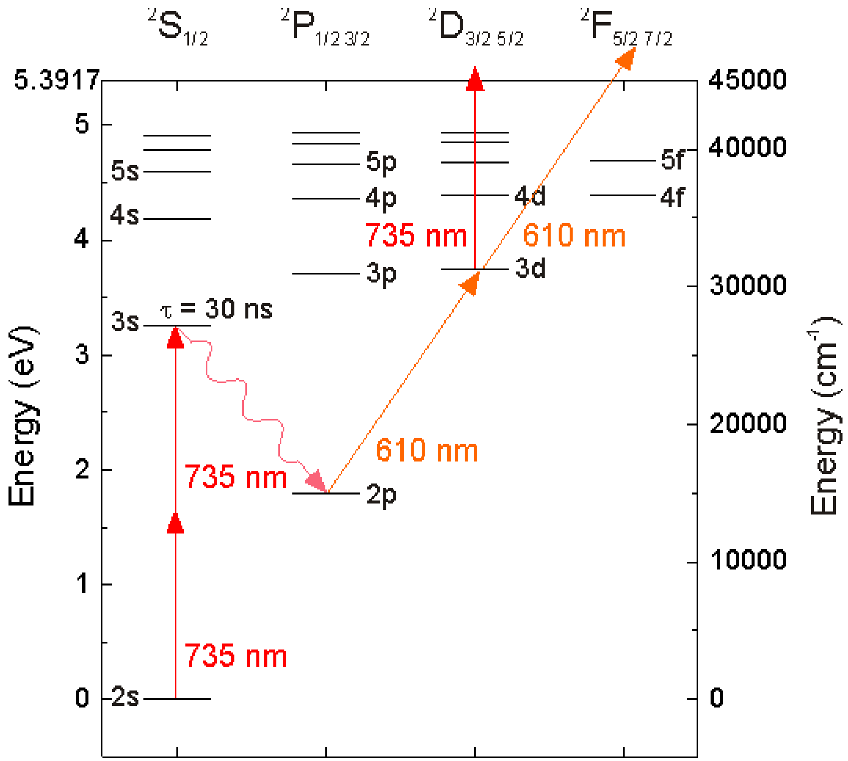


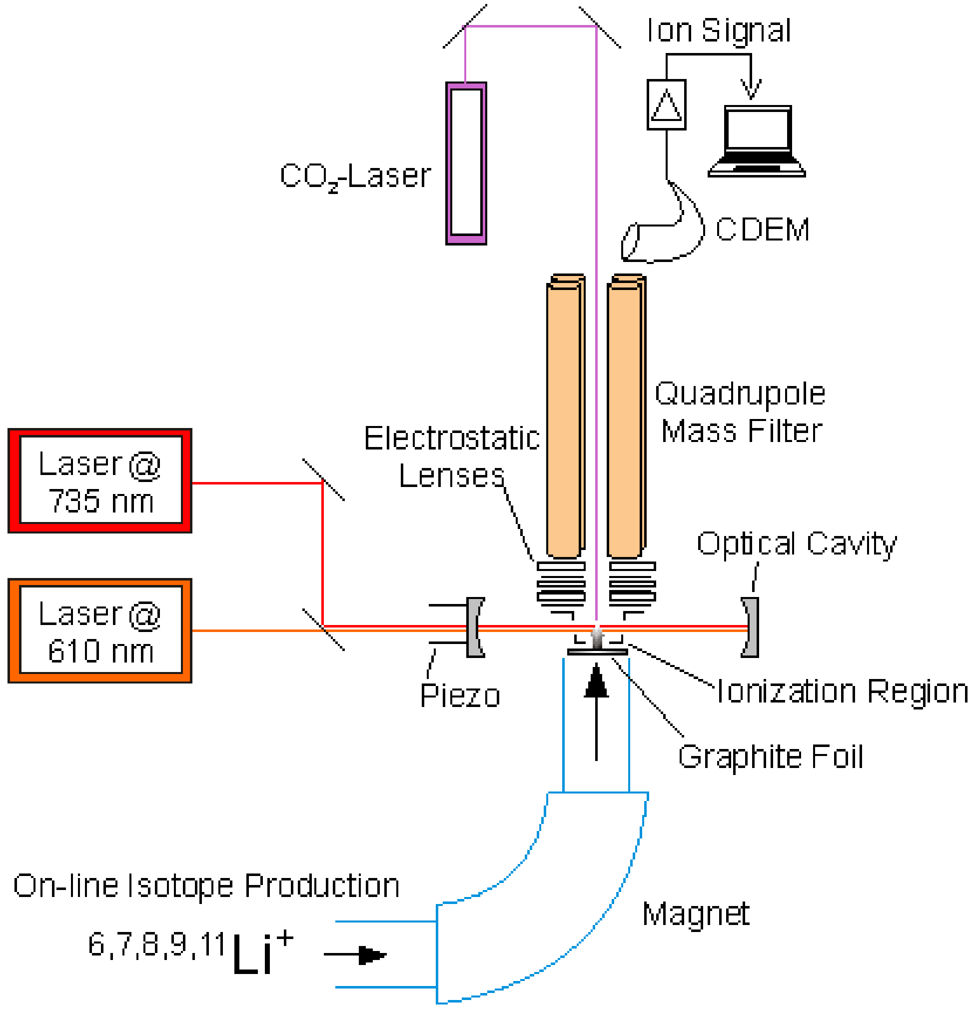
GSI

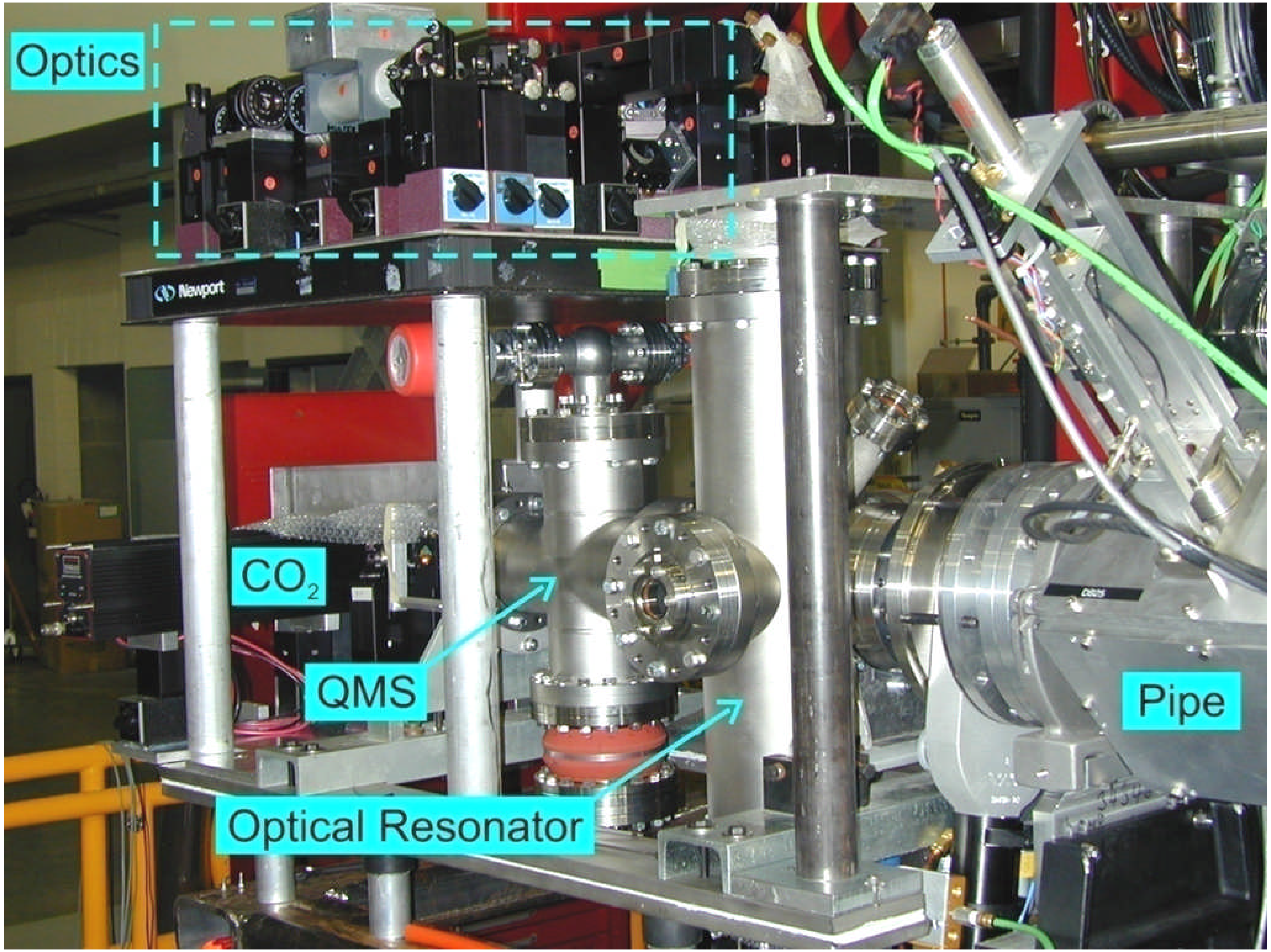
TRIUMF ISAC

Li: Experimental Technique

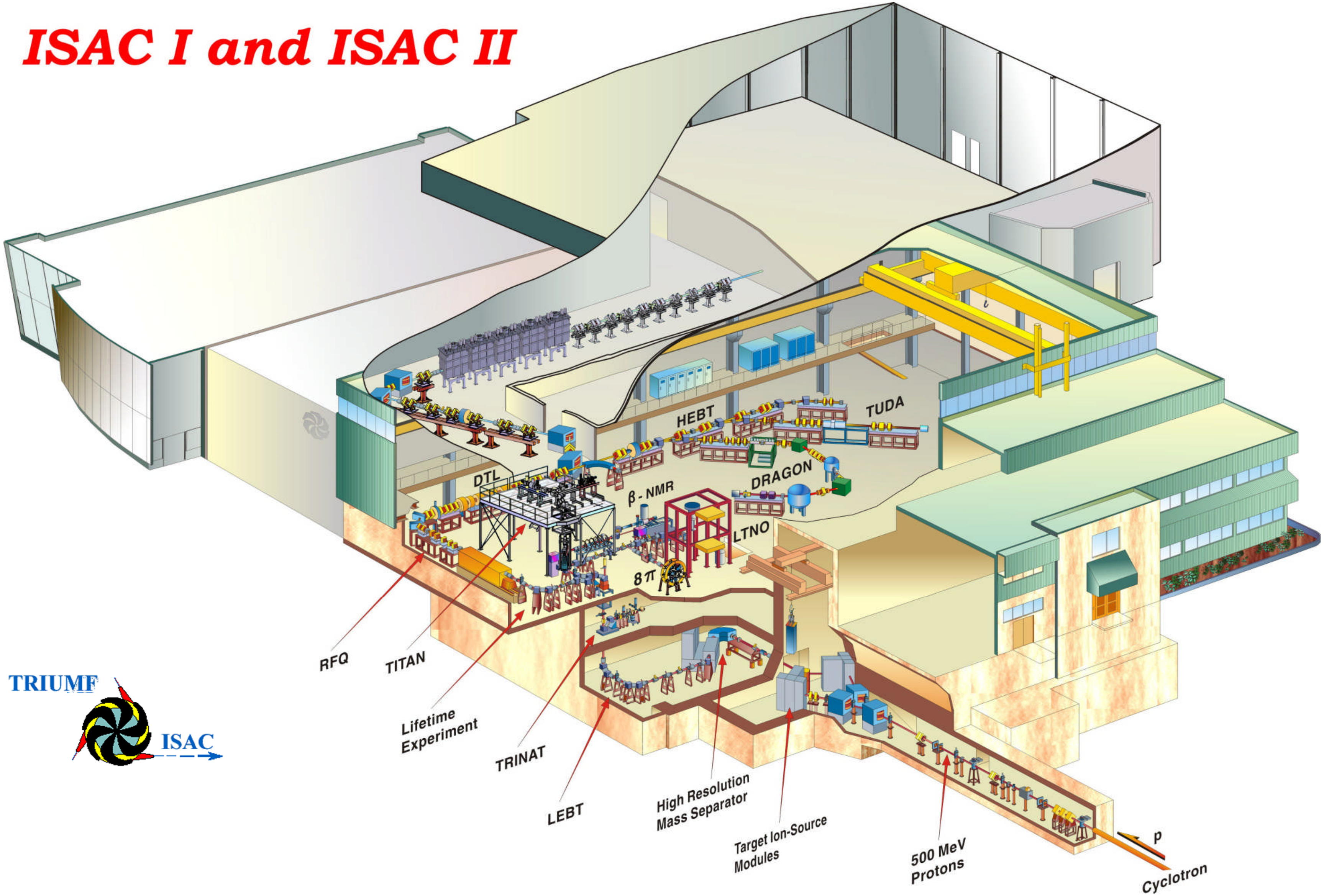
Experimentally required:
Accuracy of ~ 100 kHz
High sensitivity : $\varepsilon > 10^{-4}$
Fast technique: $T_{1/2}$ ~ s - ms






Optics
CO_2
QMS
Optical Resonator
Pipe

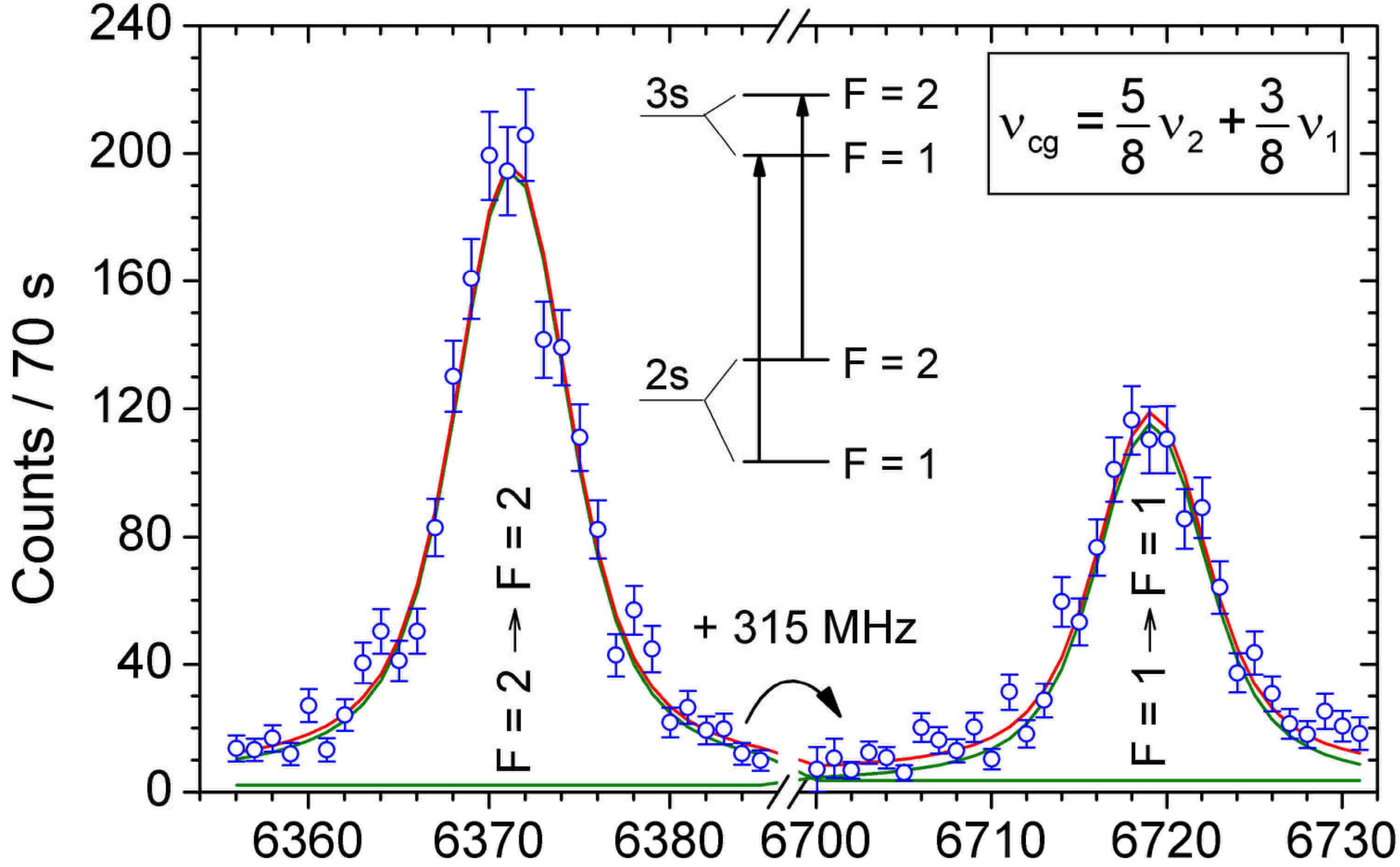
ISAC I and ISAC II



TRIUMF
ISAC

^{11}Li – Spectrum

$\delta\nu^{11,6}$ = 36 555.210 ± 0.066 (stat) ± 0.059 (syst) MHz

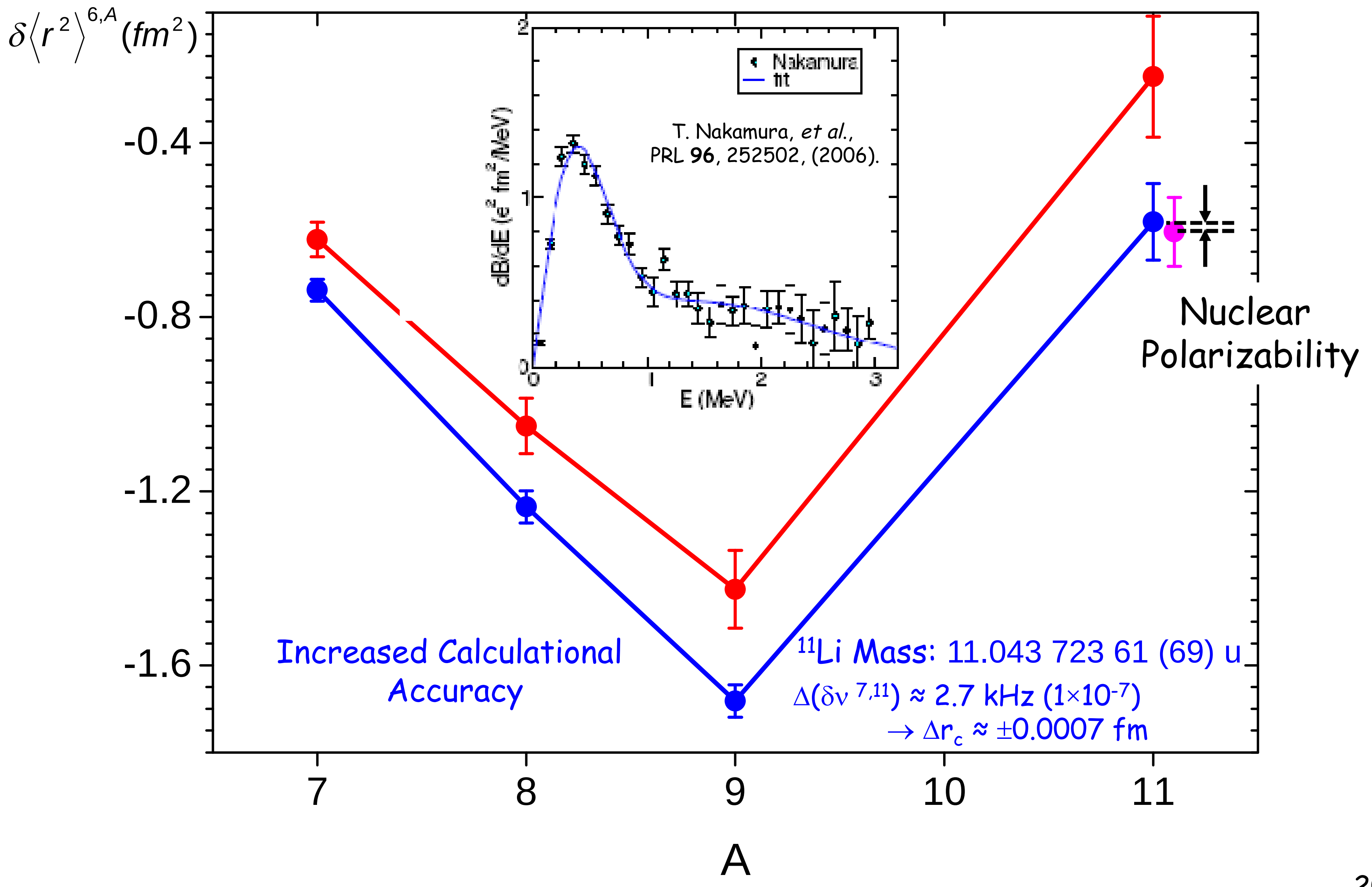


Sanchez et al. (2006): R_c (^{11}Li) = 2.467 (37) fm

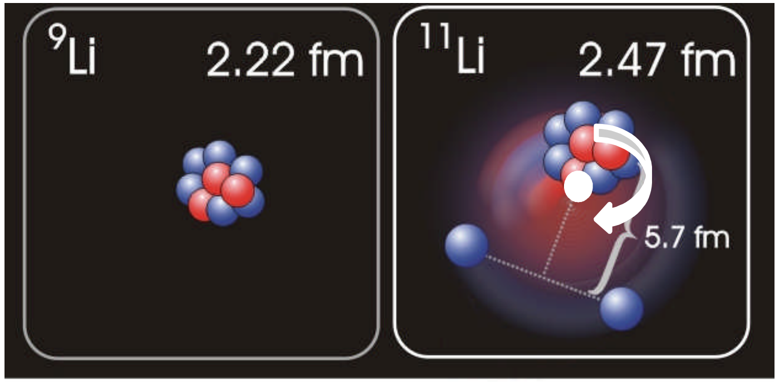
Puchalski et al. (2008): R_c (^{11}Li) = 2.426 (34) fm

?

Change in the RMS Charge Radius



Charge Radius of ^{11}Li in the Three-Body Model



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

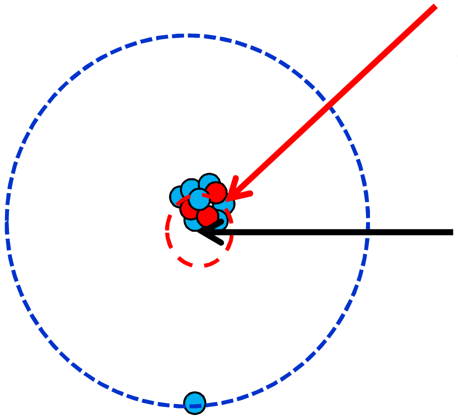
Geometrical Relation of CM-Motion:

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

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

Center-of-mass motion

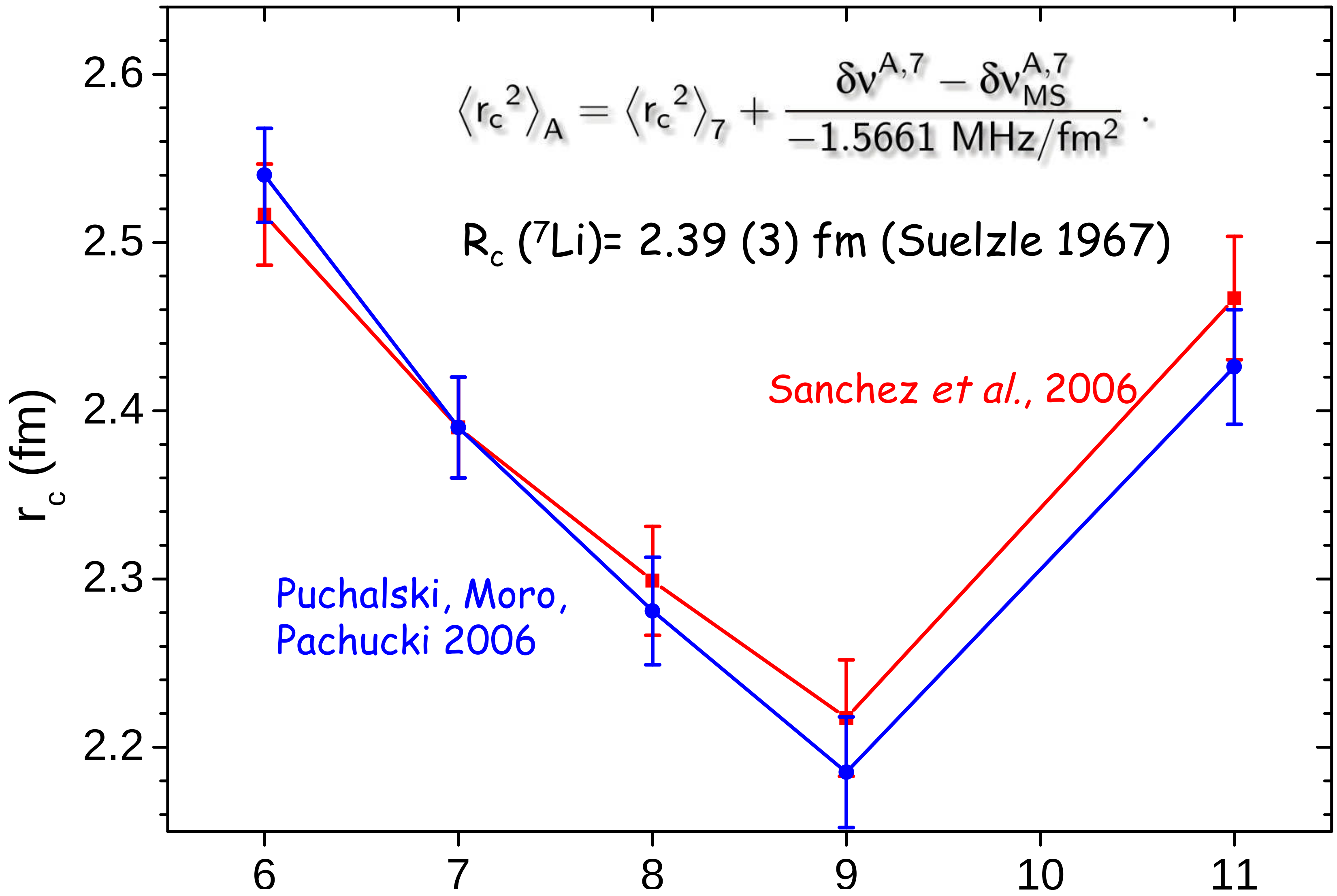
classical picture:



$$r_c(^{11}\text{Li}) = \sqrt{[R_{\mathrm{C-CM}}]^2 + [r_\mathrm{c}(^{9}\mathrm{Li})]^2}$$

Charge Radius of ^{9}Li has to be known in Advance in order to calculate the Charge Radius of ^{11}Li.

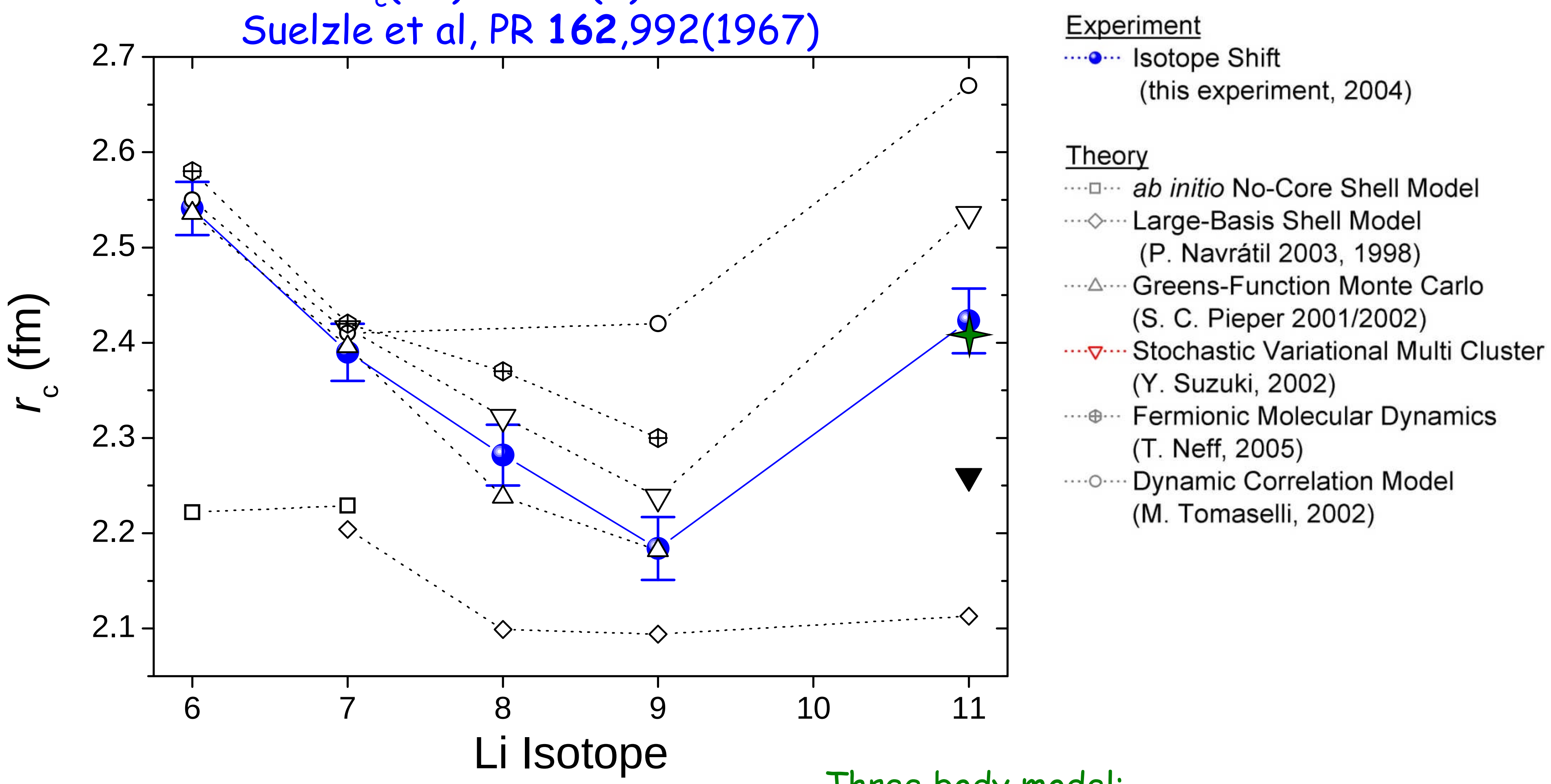
Effect on Nuclear Charge Radii



[13] R. Sanchez et al., Phys. Rev. Lett. 96 (2006) 033002.
[14] M. Puchalski, A.M. Moro, K. Pachucki, Phys. Rev. Lett. 97 (2006) 133001
[30] T. Nakamura et al., Phys. Rev. Lett. 96 (2006) 252502

Nuclear Charge Radii – Comparison with Theory

$r_c(^7Li) = 2.39(3)$ fm
Suelzle et al, PR **162**,992(1967)



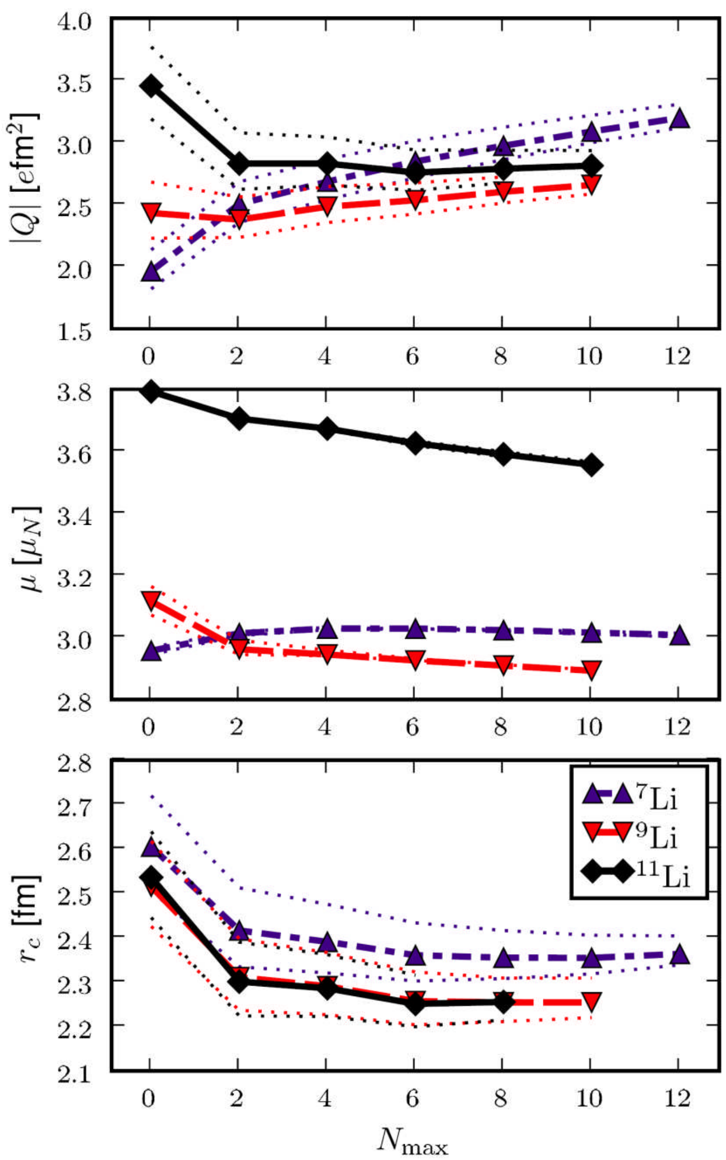
R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
M. Puchalski *et al.*, PRL 97, 133001 (2006)

Three body model:

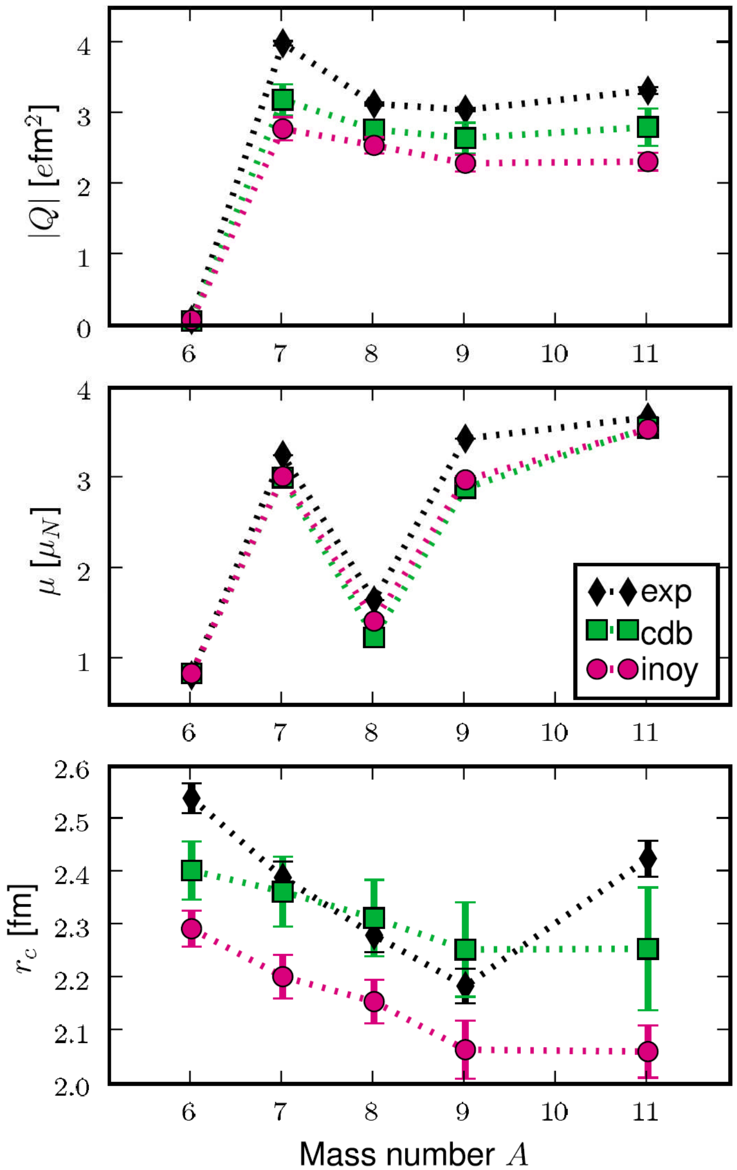
$$\sqrt{[R_{\mathrm{C-CM}}]^2 + [r_c(^9\mathrm{Li})]^2} = 2.40(6)\ \mathrm{fm}$$

Electromagnetic Moments of Li in the NCSM

C. FORSSÉN, E. CAURIER, AND P. NAVRÁTIL



PHYSICAL REVIEW C 79, 021303(R) (2009)



Charge Radius and Dipole Response

PHYSICAL REVIEW C **76**, 024302 (2007)

Charge radius and dipole response of ^{11}Li

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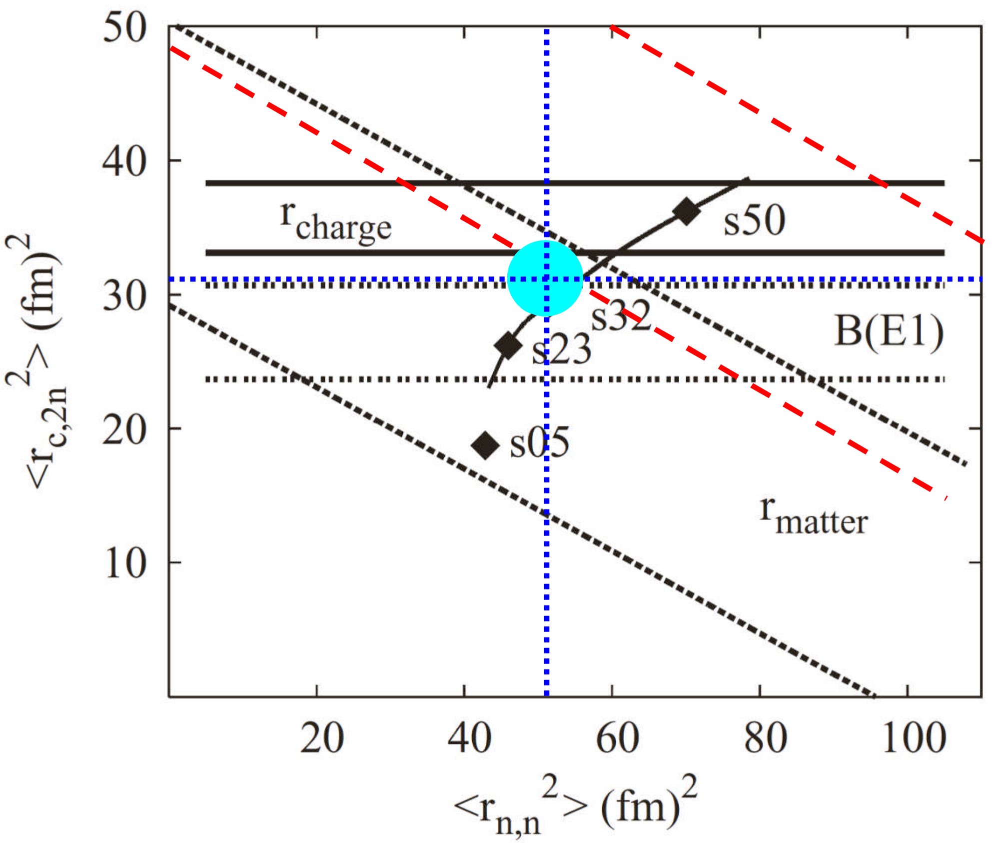
[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[3]*Center for Mathematical Sciences, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8560, Japan*
(Received 27 April 2007; published 1 August 2007)



$$\delta\langle r_{ch}^2\rangle = \langle r_{ch}^2(Z,A)\rangle - \langle r_{ch}^2(Z,A-2)\rangle$$
$$= \left(\frac{2}{A}\right)^2 \langle r_{c,2n}^2\rangle - \frac{0.232}{Z} + \langle r^2\rangle_{2n}^{so}.$$

$$\langle r_m^2(Z,A)\rangle = \frac{A-2}{A}\langle r_m^2(Z,A-2)\rangle + \frac{2(A-2)}{A^2}\langle r_{c,2n}^2\rangle + \frac{1}{2A}\langle r_{n,n}^2\rangle.$$

R_m (^{9}Li) = 2.43(2) fm
R_m (^{11}Li) = 3.27(24) fm
I. Tanihata *et al.*, *PRL* ***55***, *2676 (1985).*

R_m (^{11}Li) = 3.55(10) fm
J.S. Al-Khalili and J.A. Tostevin, *PRL* ***76***, *3903 (1996).*

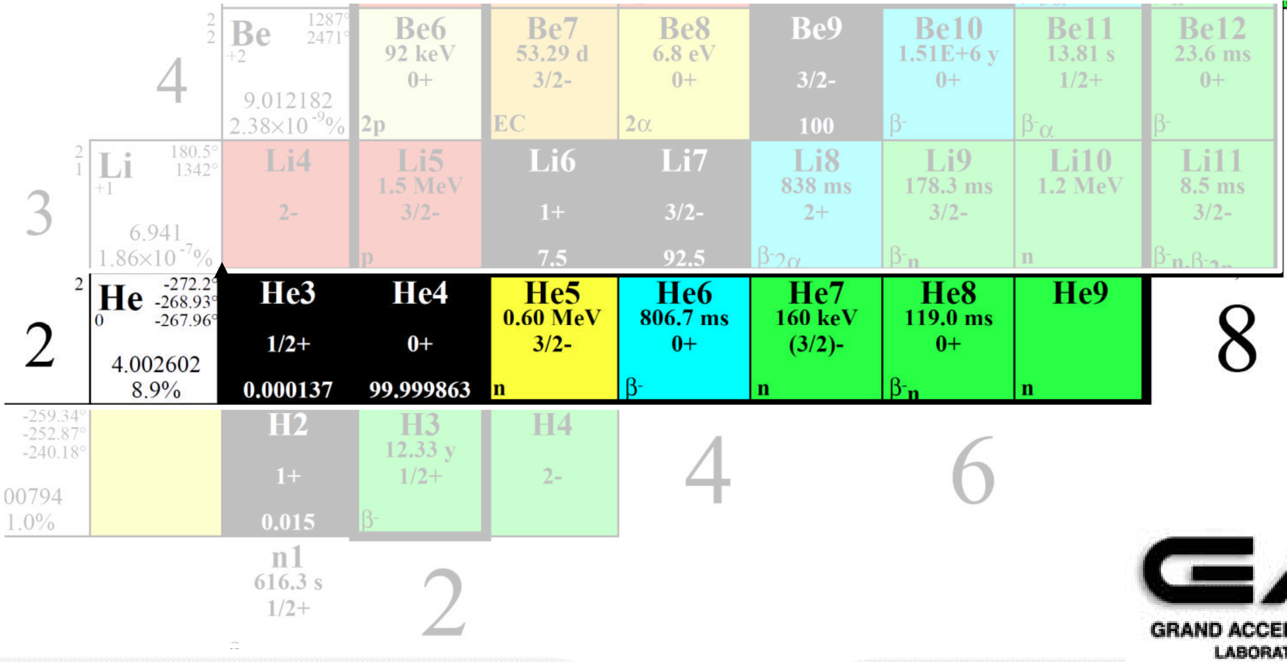
R_m (^{11}Li) = 3.42(11) fm
A.V. Dobrovolsky *et al.*, *Nucl. Phys. A* ***766***, *1 (2006).*

Component	Percentage (%)
$s_{1/2}, s_{1/2}$	36.8
$p_{1/2}, p_{1/2}$	46.8
$p_{3/2}, p_{3/2}$	9.9
$s_{1/2}, d_{3/2,5/2}$	3.7
$p_{1/2}, p_{3/2}$	2.8
$J_{halo} = 0$	93.4
$J_{halo} = 1, 2$	6.6

Shulgina *et al.*, Nucl. Phys. A **825**, 175 (2009).

Case 2: Helium

Laser SpHERe

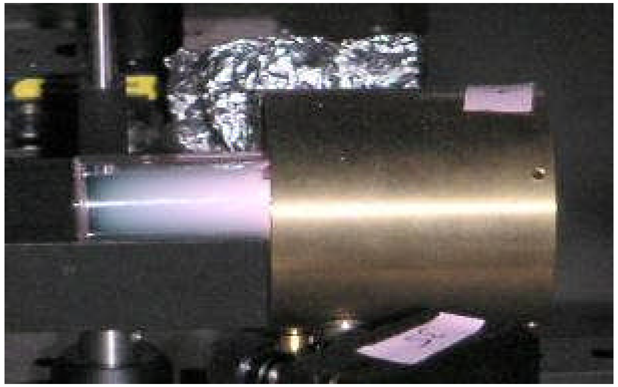


GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS

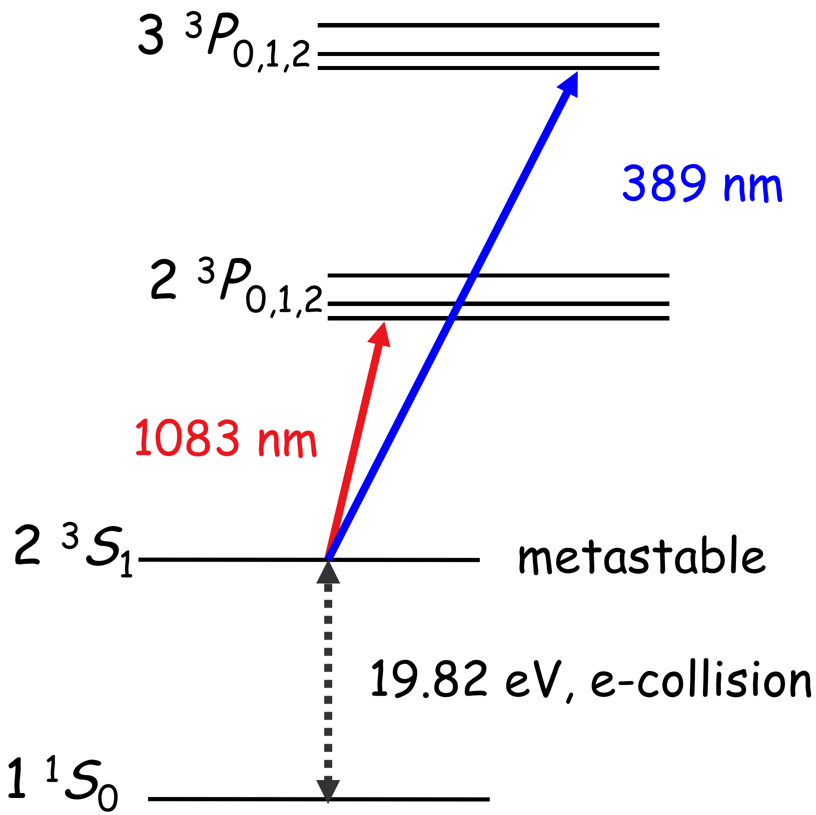
Argonne NATIONAL LABORATORY

Atomic Energy Levels of Helium

He discharge



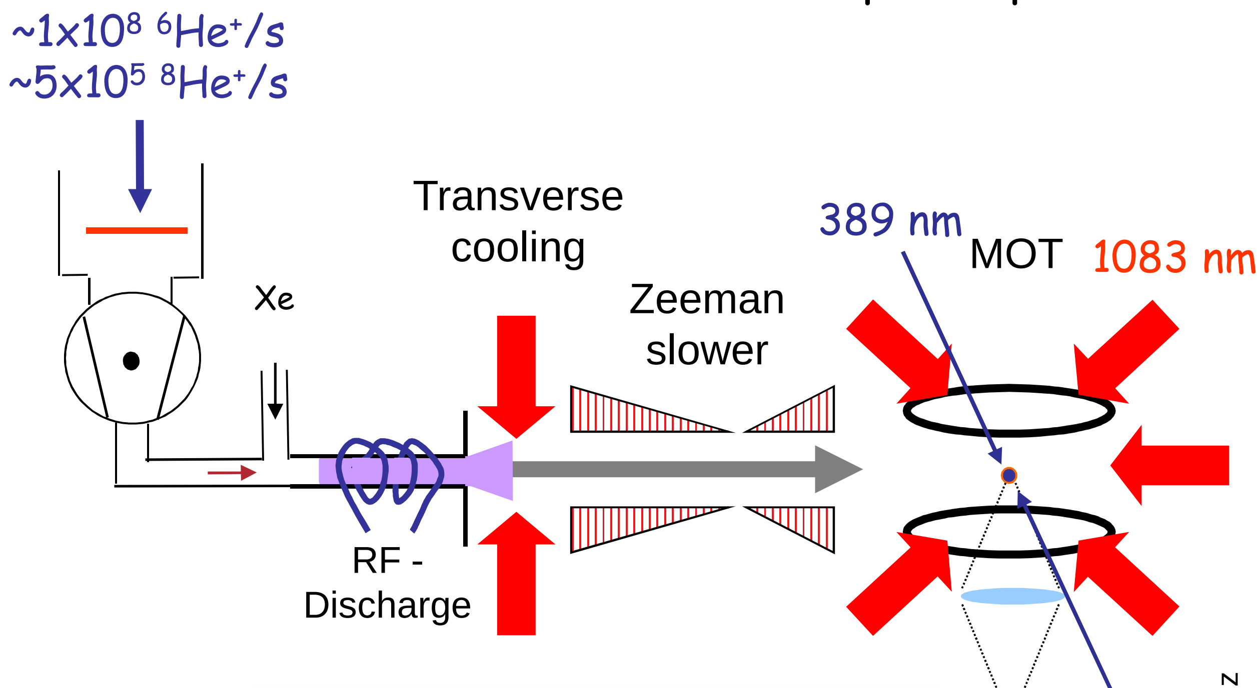
He energy level diagram

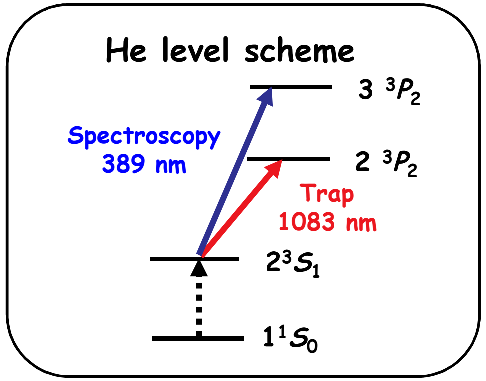


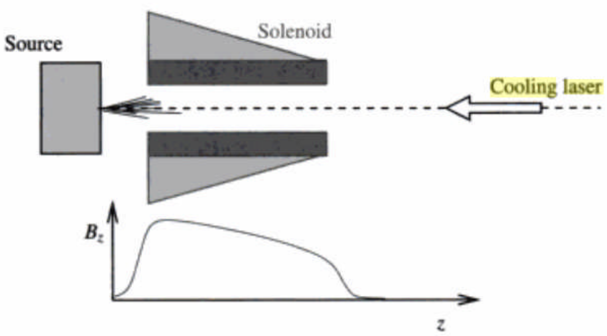
Spectroscopy from metastable state populated by discharge

Atom Trapping of ^6He & ^8He at GANIL

Atom Trap Setup

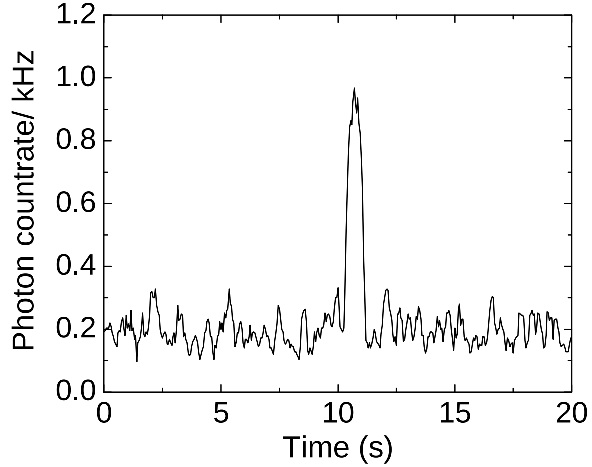




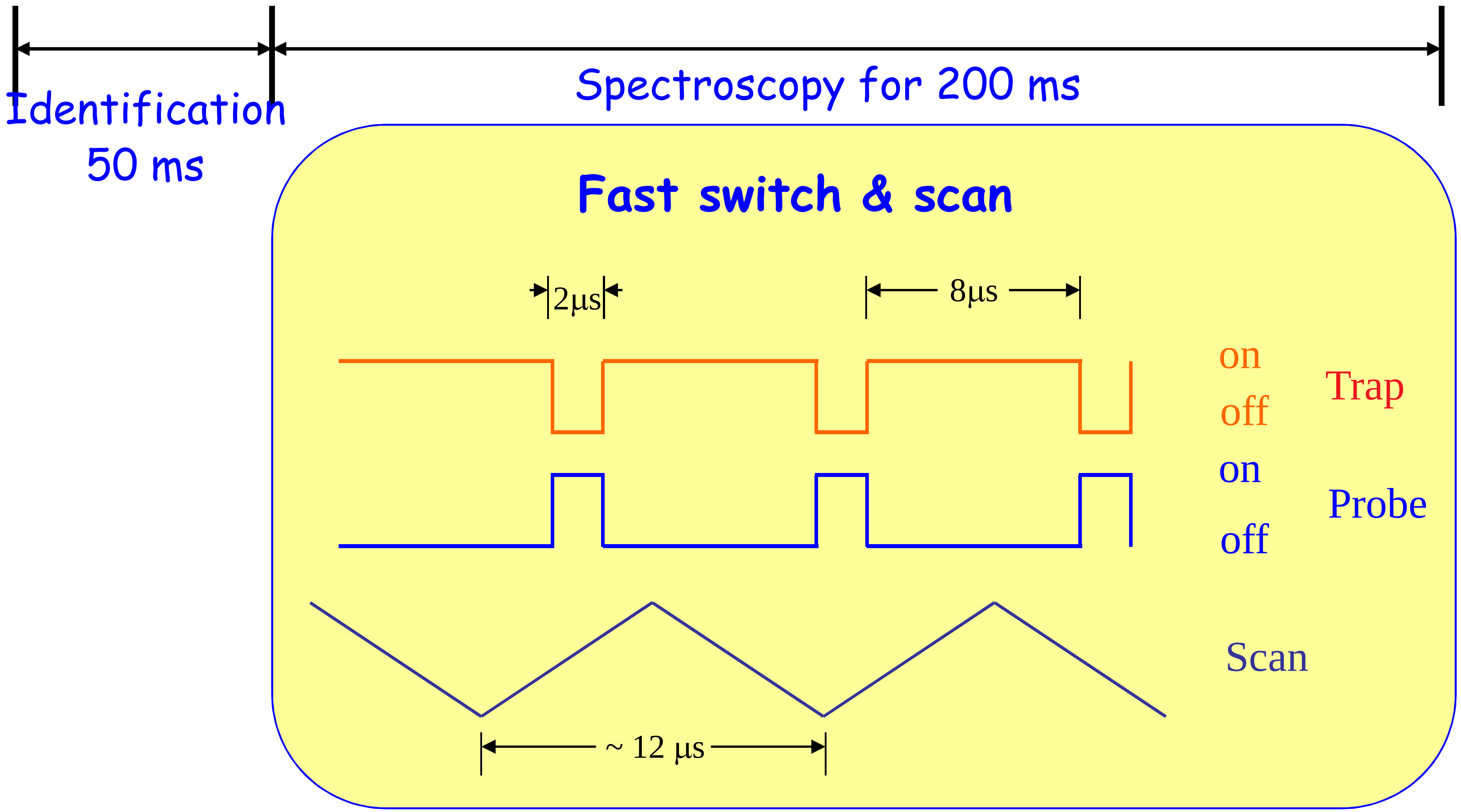


Metcalf, van der Straaten: „Laser Cooling and Trapping", Springer Verlag

One trapped ^6He atom

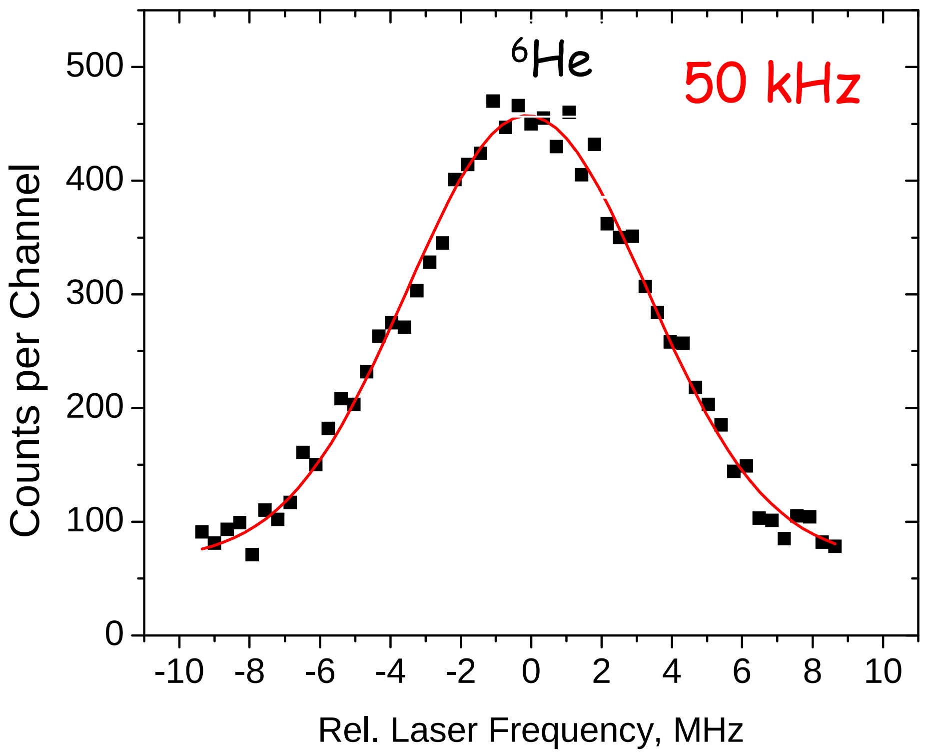


Switch & Scan

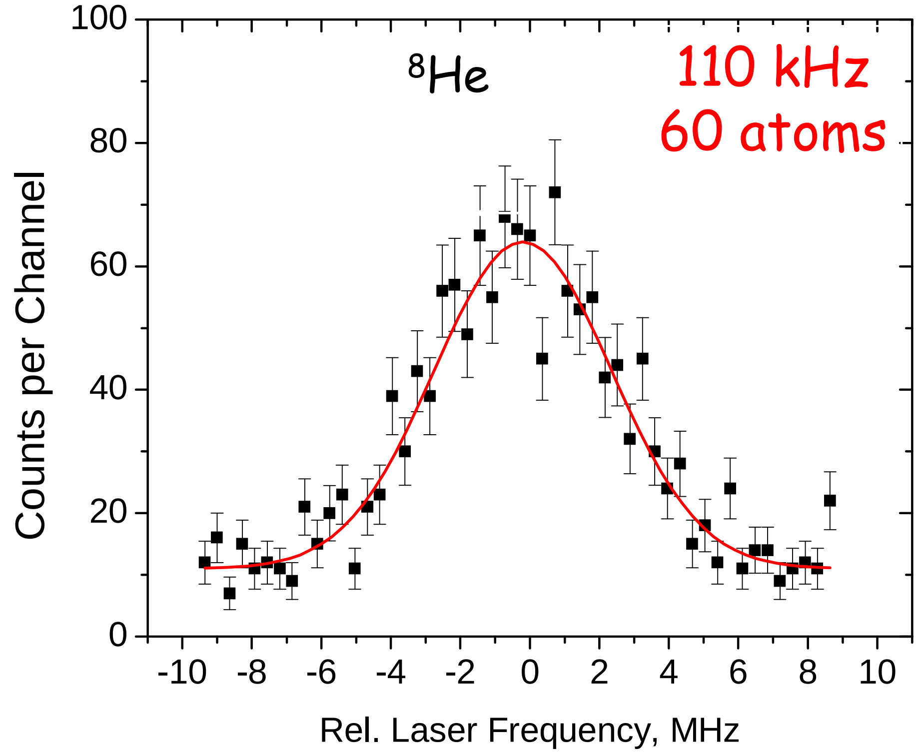


❖ Power balance between the two opposing probe beams

Helium Resonances

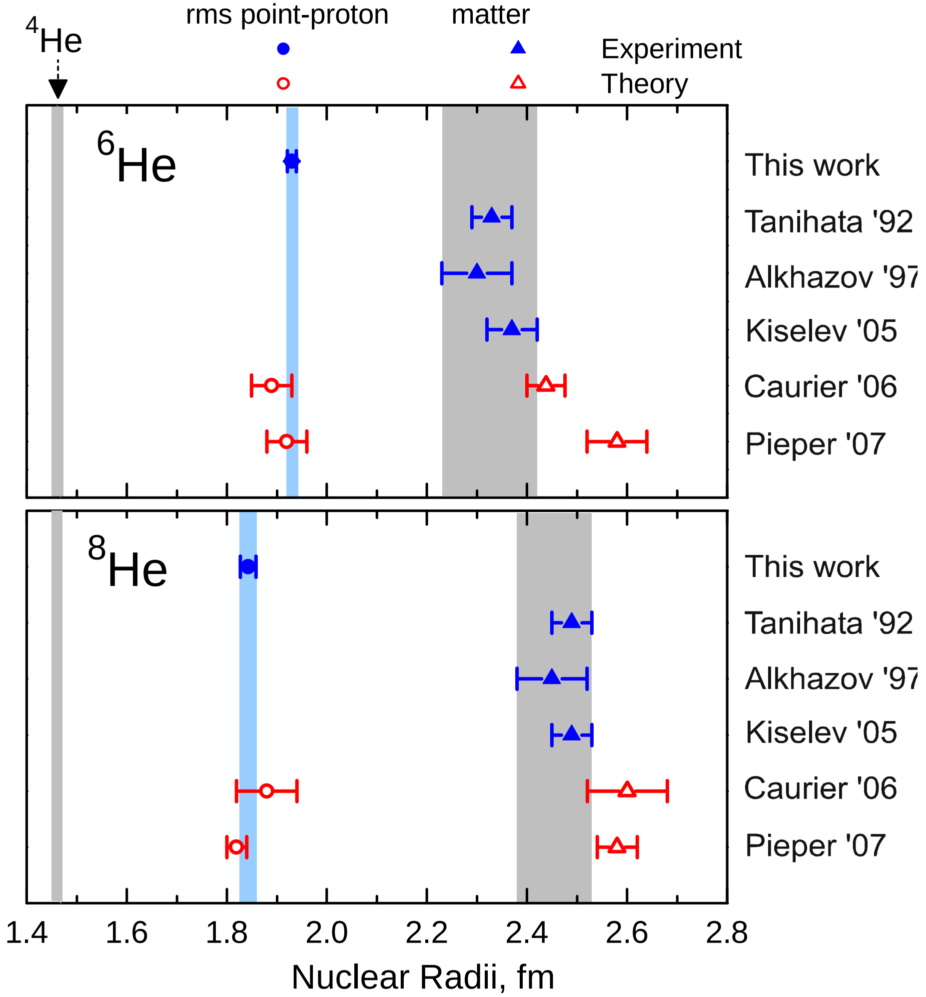


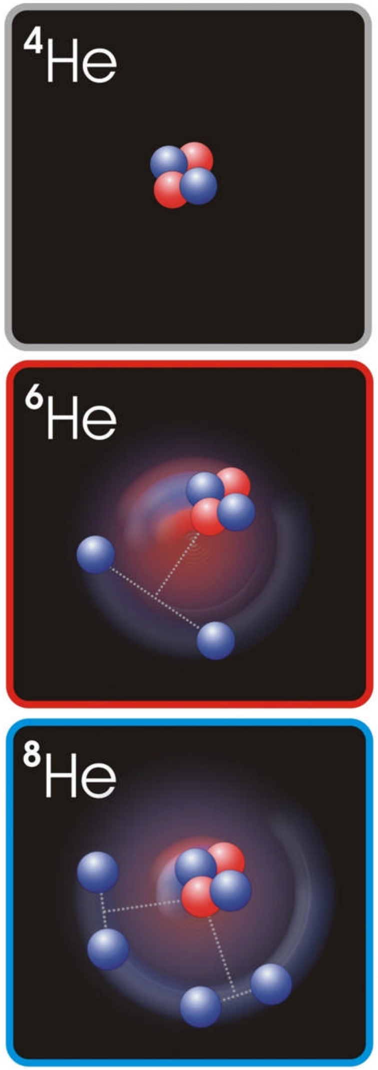
~ 5 ^6He atoms/s



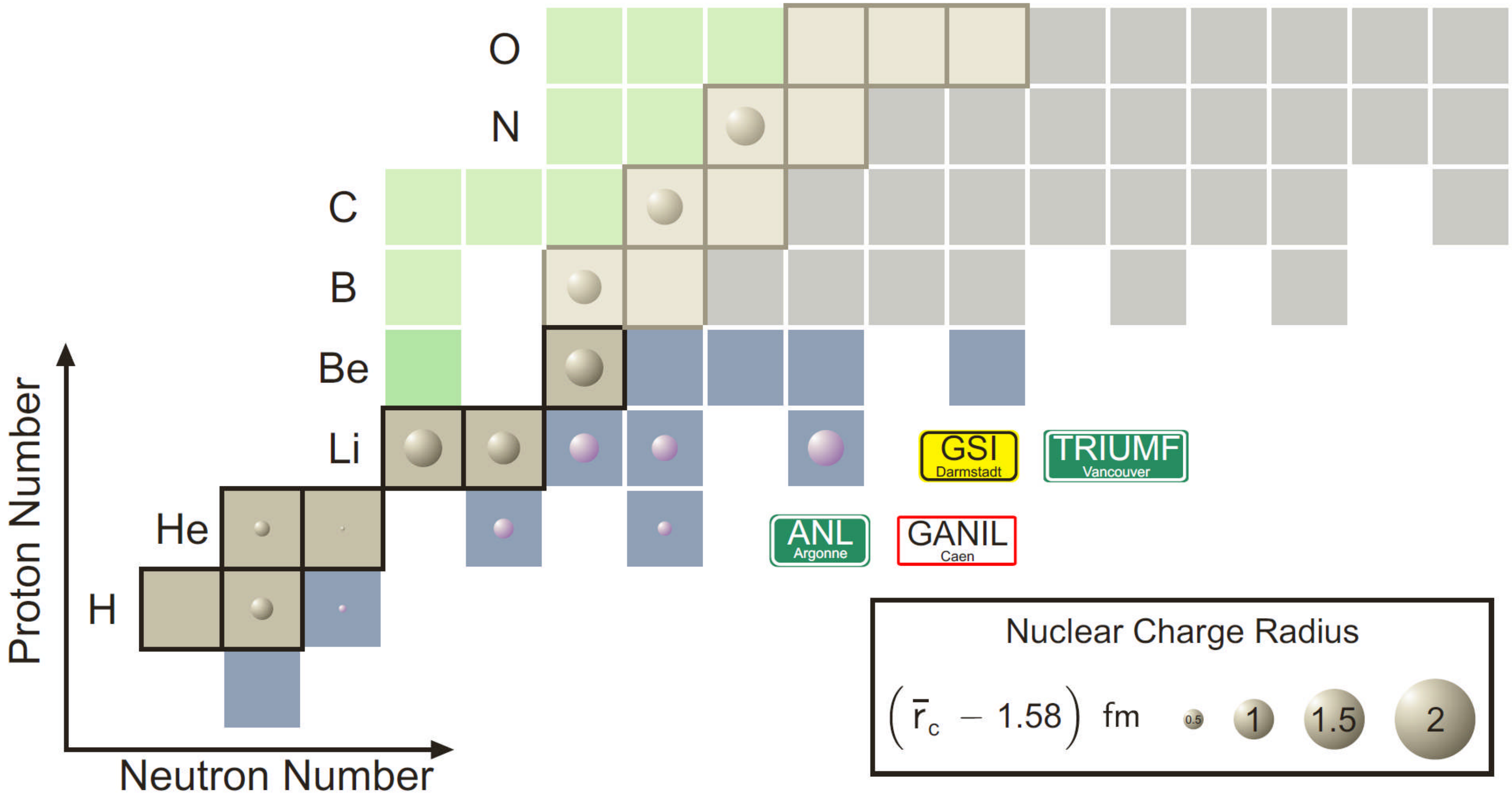
~ 30 ^8He atoms/hr

^{6}He & ^{8}He RMS Point Proton and Matter Radii





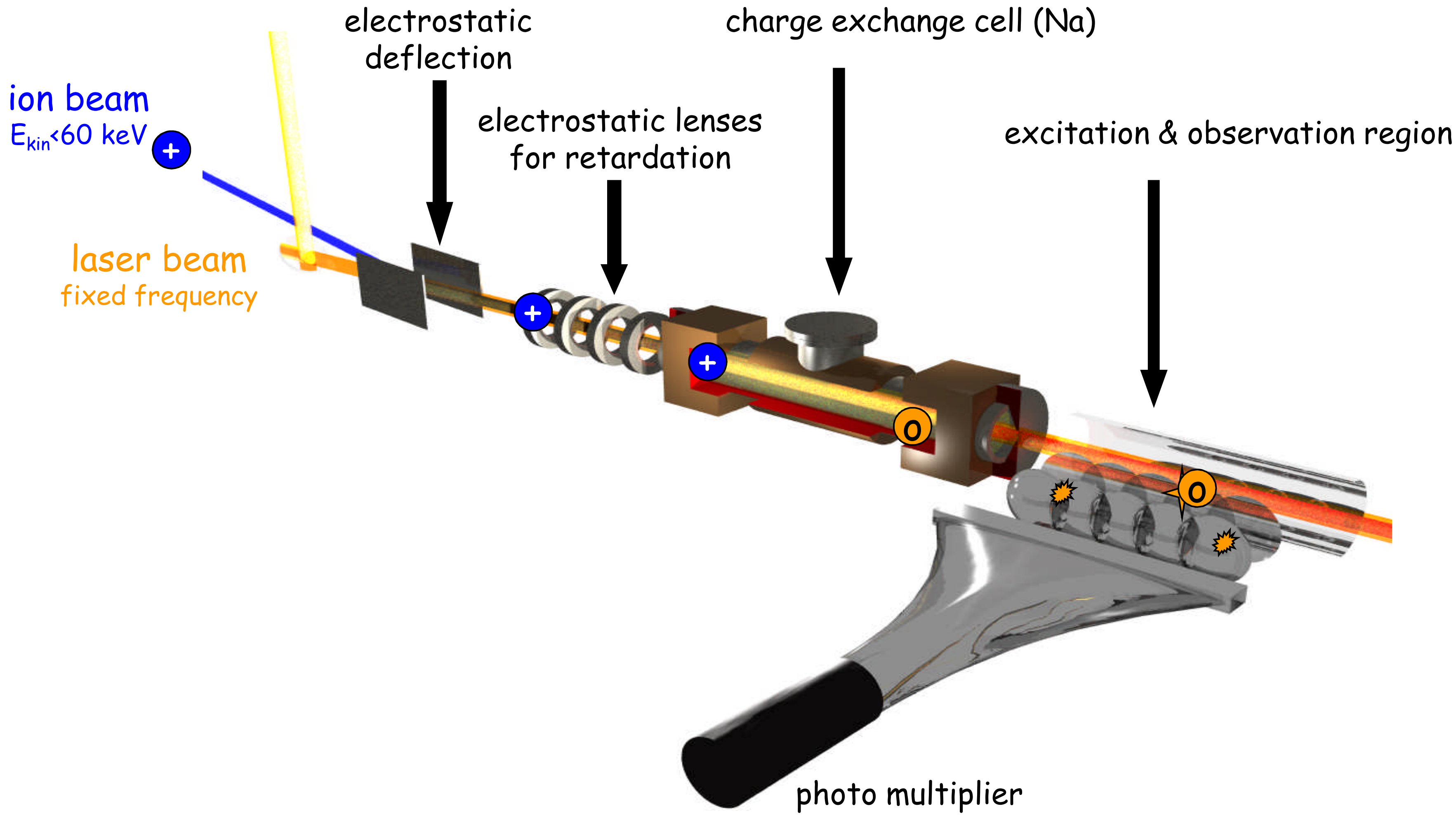
The Next Step: Z=4 Beryllium



Atomic Structure Calculations ($N_{e-} \leq 3$)
→ Be^{+}

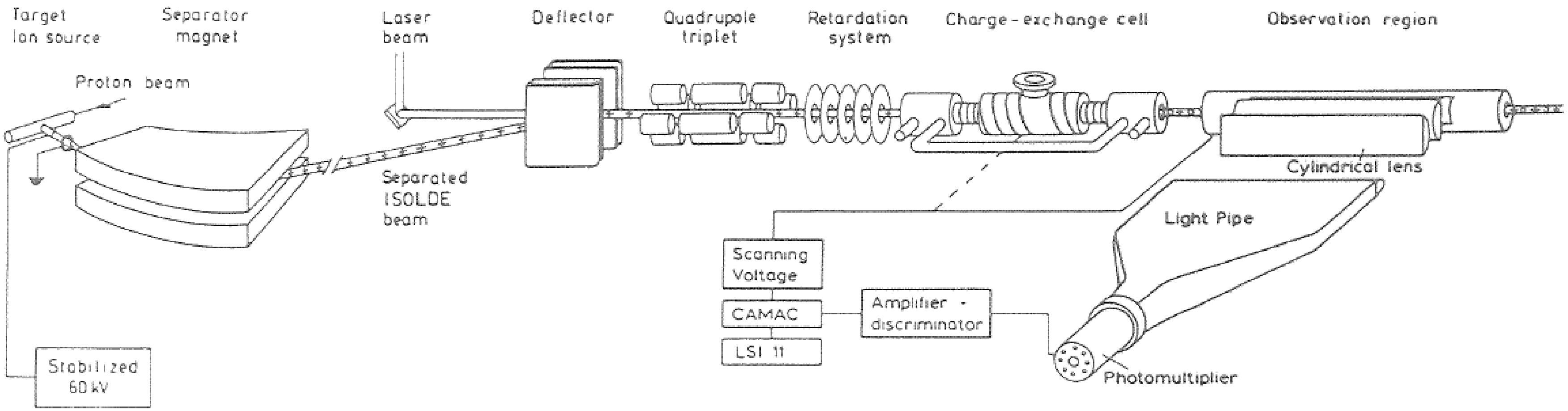
Ewald, Sánchez, Nörtershäuser *et al.* 2004, 2006
Wang, Müller *et al.* 2005, 2007

Collinear Laser Spectroscopy
The Principle

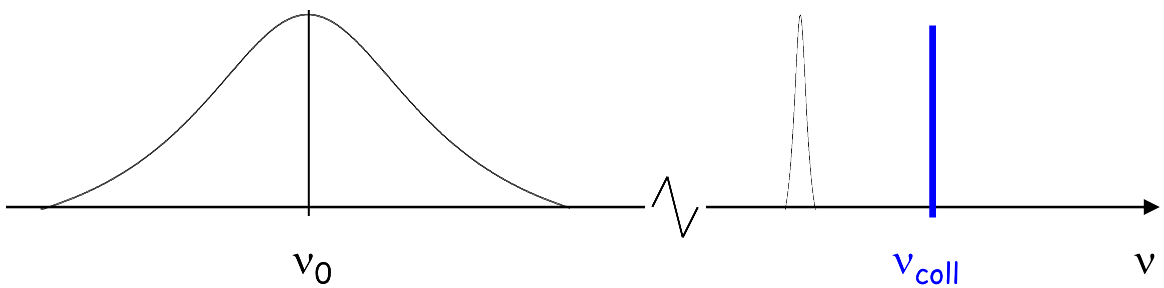


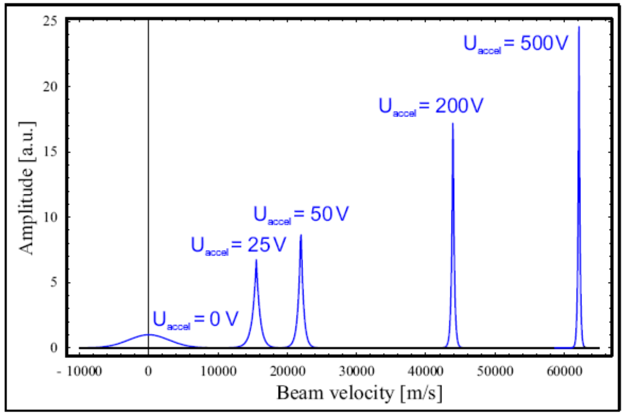
Collinear Laser Spectroscopy

The Principle



S.L. Kaufman, Opt. Comm. **17** (1976) 309. K.-R. Anton, PRL **40** (1978) 642
T. Meier et al., Opt. Comm. **20** (1977) 397 E.W. Otten, *Nuclear Radii and Moments of unstable Isotopes (1989)*





$$E = eU = 1/2\, m\upsilon^2$$
$$\delta E = m\upsilon\, \delta\upsilon$$

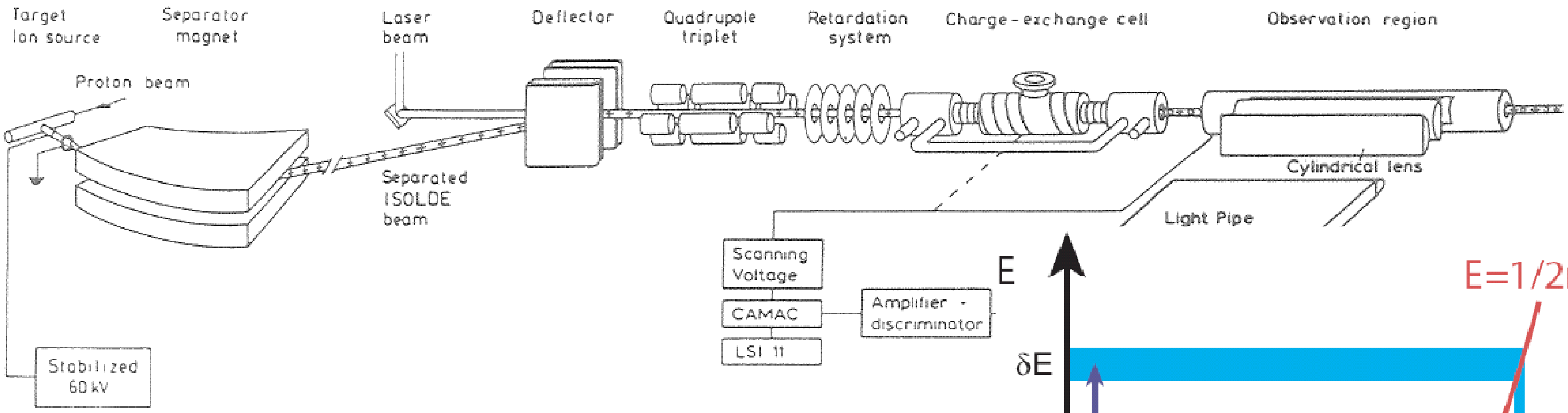
$\rightarrow$

$$\delta\nu = \nu_0\, \delta\upsilon / c = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

Doppler width
20-40 MHz

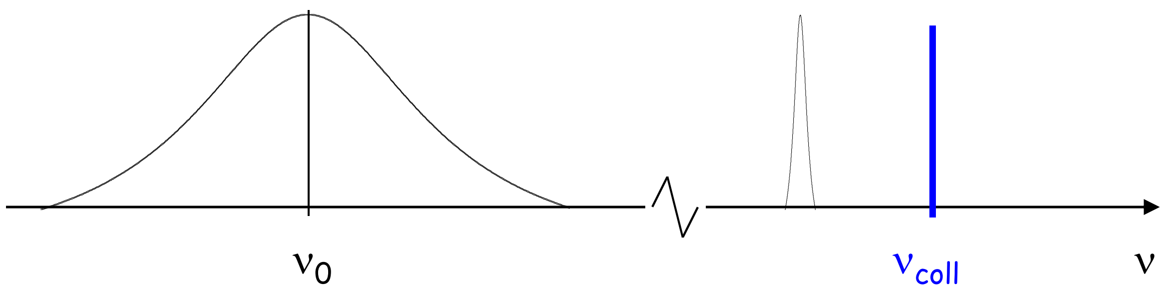
Collinear Laser Spectroscopy

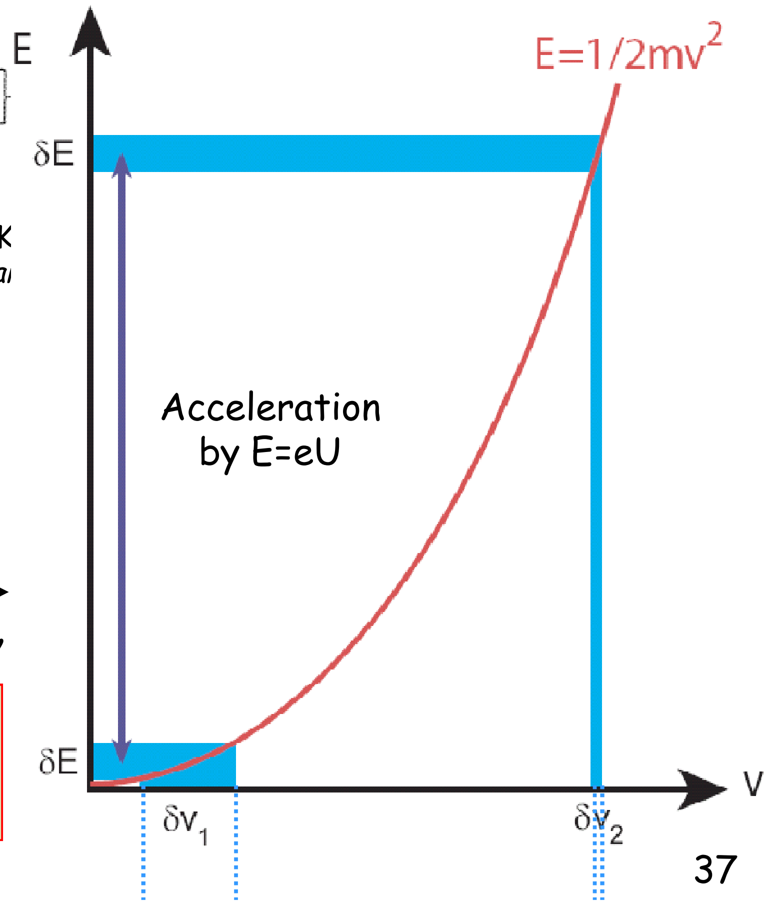
The Principle



S.L. Kaufman, Opt. Comm. **17** (1976) 309. K

T. Meier et al., Opt. Comm. **20** (1977) 397 E.W. Otten, *Nuclea*



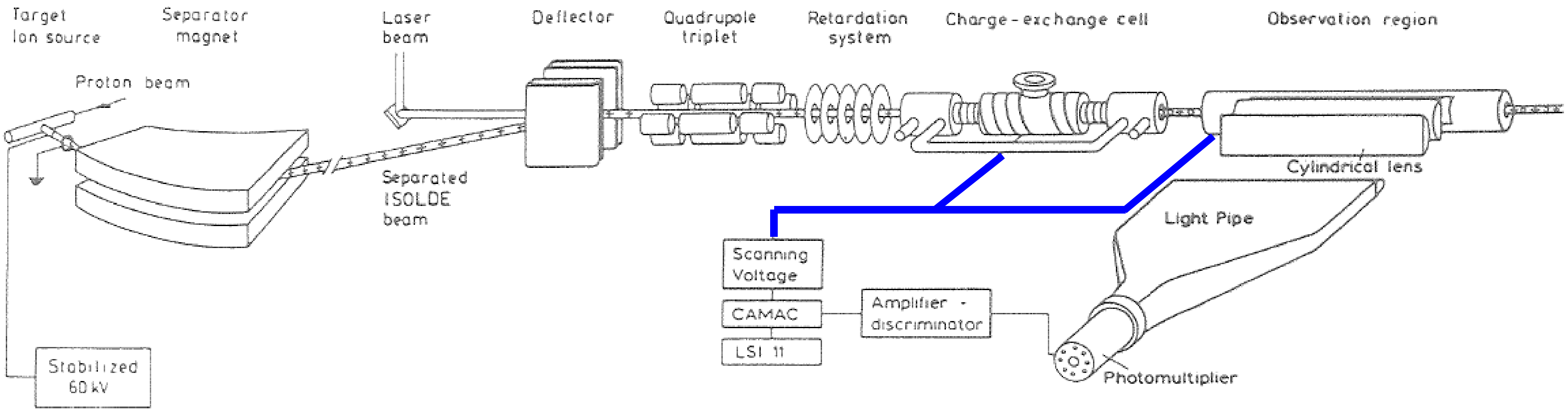


$$E = eU = 1/2\, m\upsilon^2$$
$$\delta E = m\upsilon\, \delta\upsilon$$

$$\rightarrow \quad \delta\nu = \nu_0\, \delta\upsilon / c = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

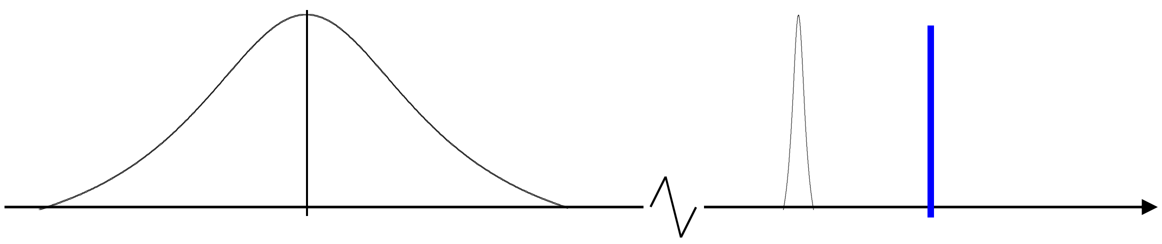
Collinear Laser Spectroscopy

The Principle



S.L. Kaufman, Opt. Comm. **17** (1976) 309. K.-R. Anton, PRL **40** (1978) 642

T. Meier et al., Opt. Comm. **20** (1977) 397 E.W. Otten, *Nuclear Radii and Moments of unstable Isotopes (1989)*



Doppler-tuning :

$$\nu_0 = \nu_L \frac{1-\beta}{\sqrt{1-\beta^2}} = \nu_L\, \gamma\, (1-\beta)$$

$$\beta = \upsilon/c = \sqrt{2eU/m}$$

$$E = eU = 1/2\, m\upsilon^2$$

$$\delta E = m\upsilon\, \delta\upsilon$$

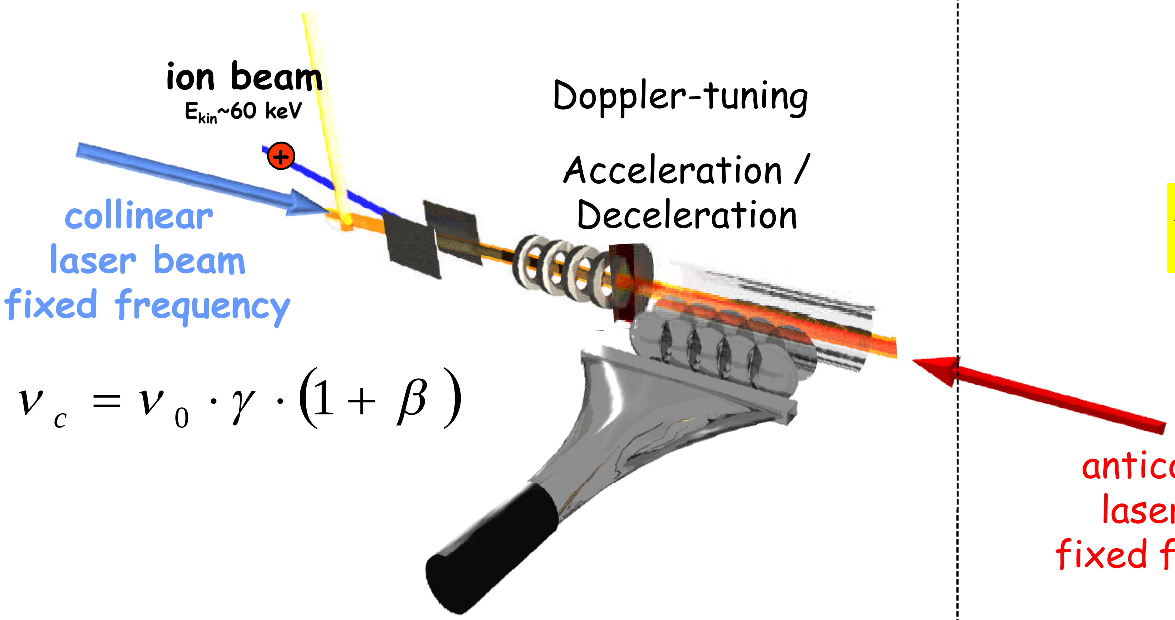
$$\rightarrow \quad \delta\nu = \nu_0\, \delta\upsilon/c = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

Doppler width
20-40 MHz

Limitations for Light Elements

The Solution

„CONVENTIONAL SETUP"



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

$\gamma = \gamma(U,m)$, $\beta = \beta(U,m)$,

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

$\Rightarrow \delta\nu_{IS}$ (^{9}Be,^{11}Be) = 14 MHz

Impossible for Light Elements (Z<10) !!

NEW APPROACH

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

anticollinear laser beam fixed frequency

Completely independent of U !

Requirements:

Measure absolute frequencies

Accuracy: $\Delta\nu/\nu < 10^{-9}$

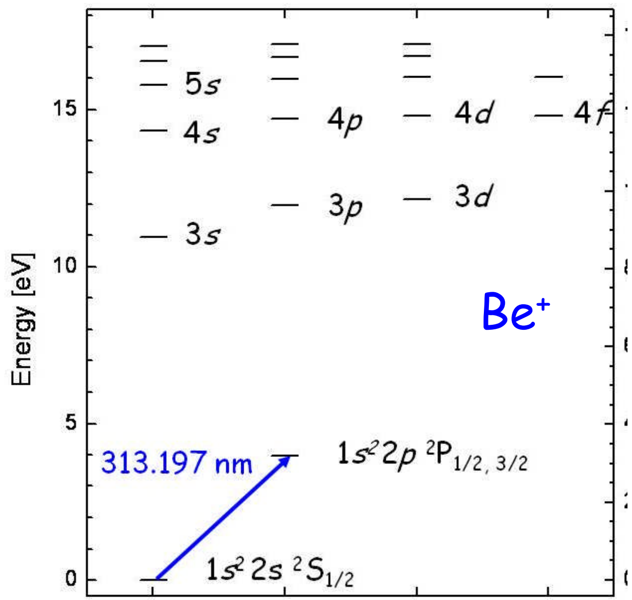
Dedicated Laser System for absolute Frequency Measurements

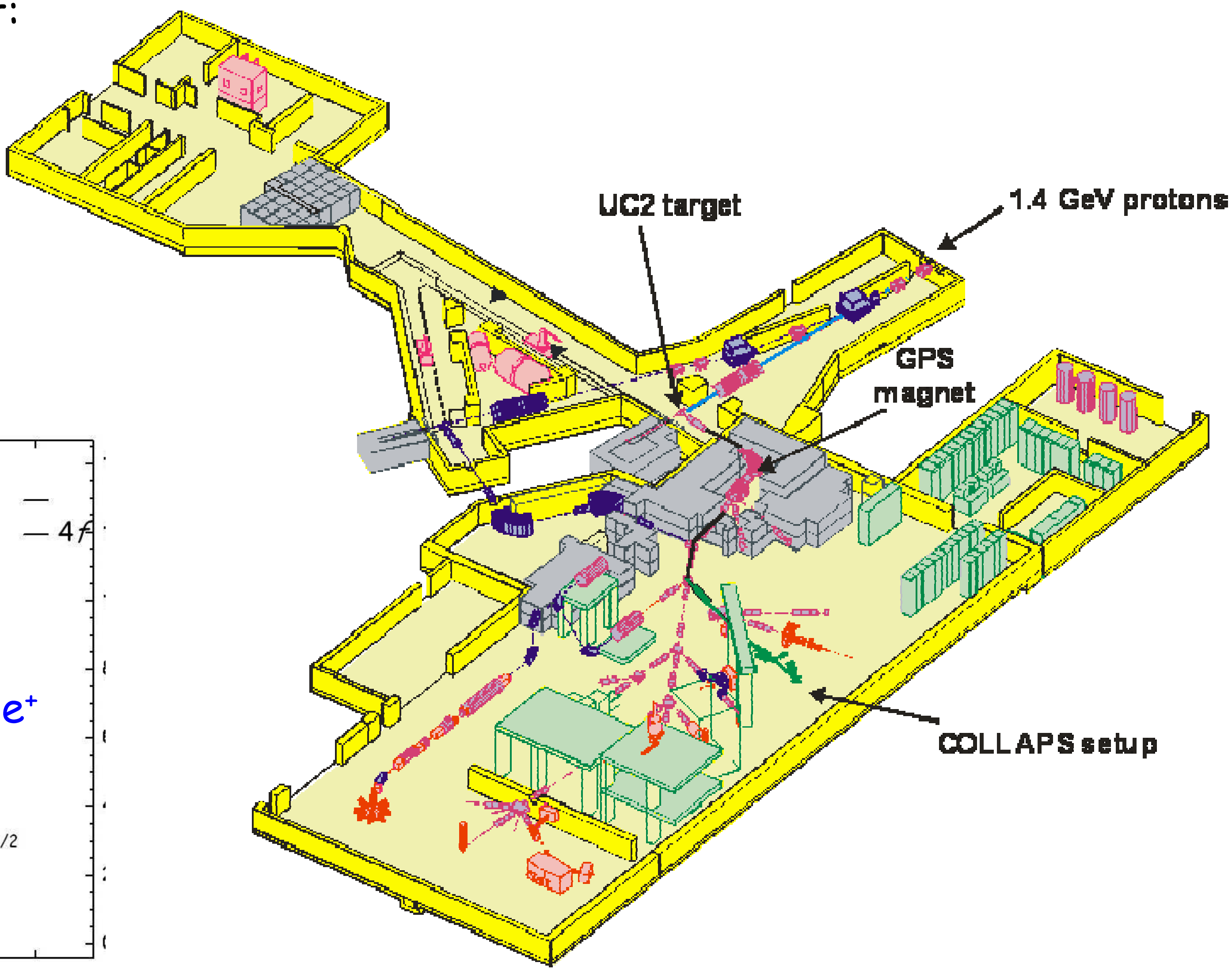
Production of Be Isotopes

Development and Test:
Mainz (2005-2008)

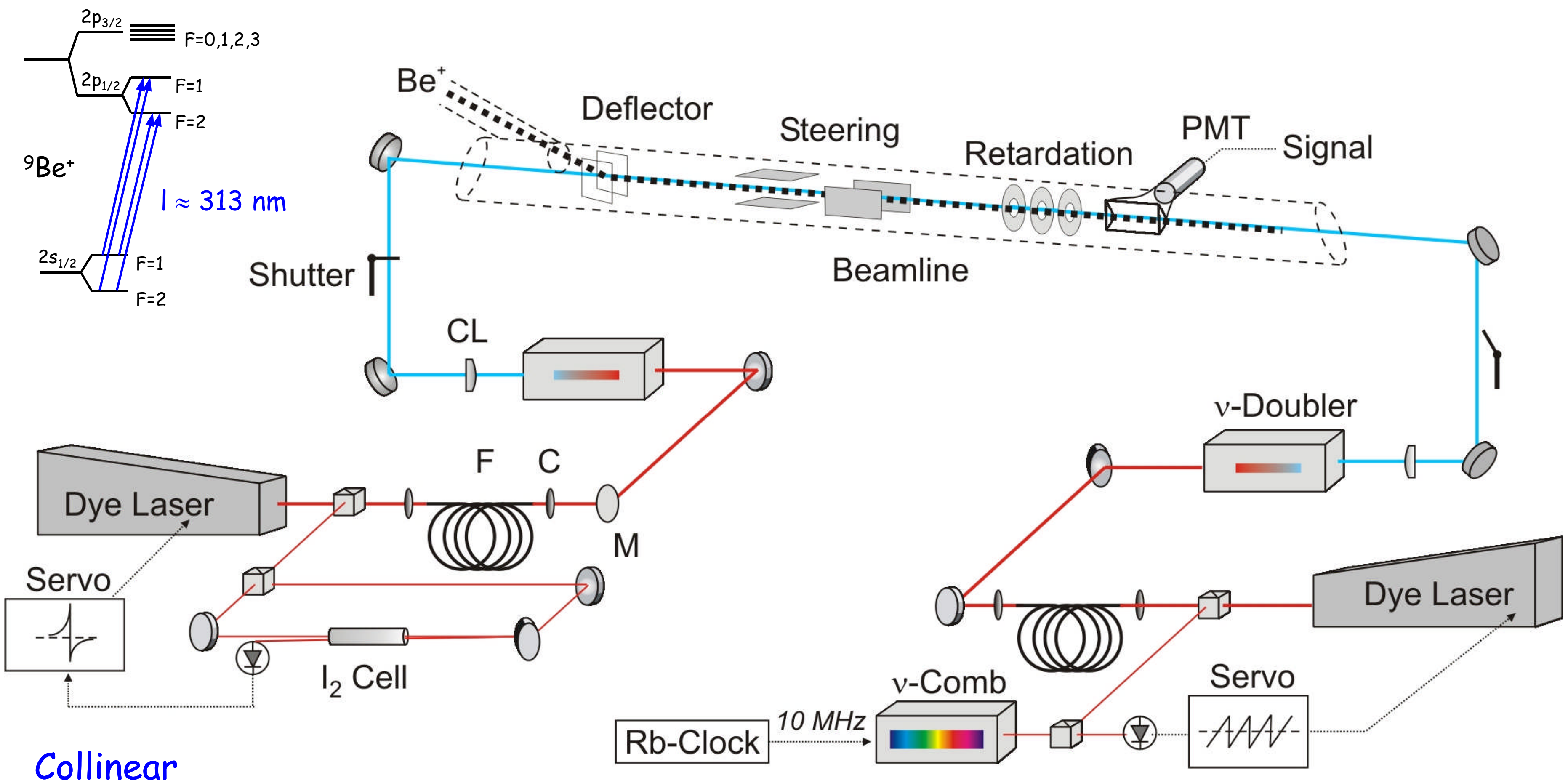
Experiment on ^{11}Be:
ISOLDE (CERN)

~ 10^6 - 10^7 $^{11}Be^+$/s
$T_{1/2}$ = 13.6 s





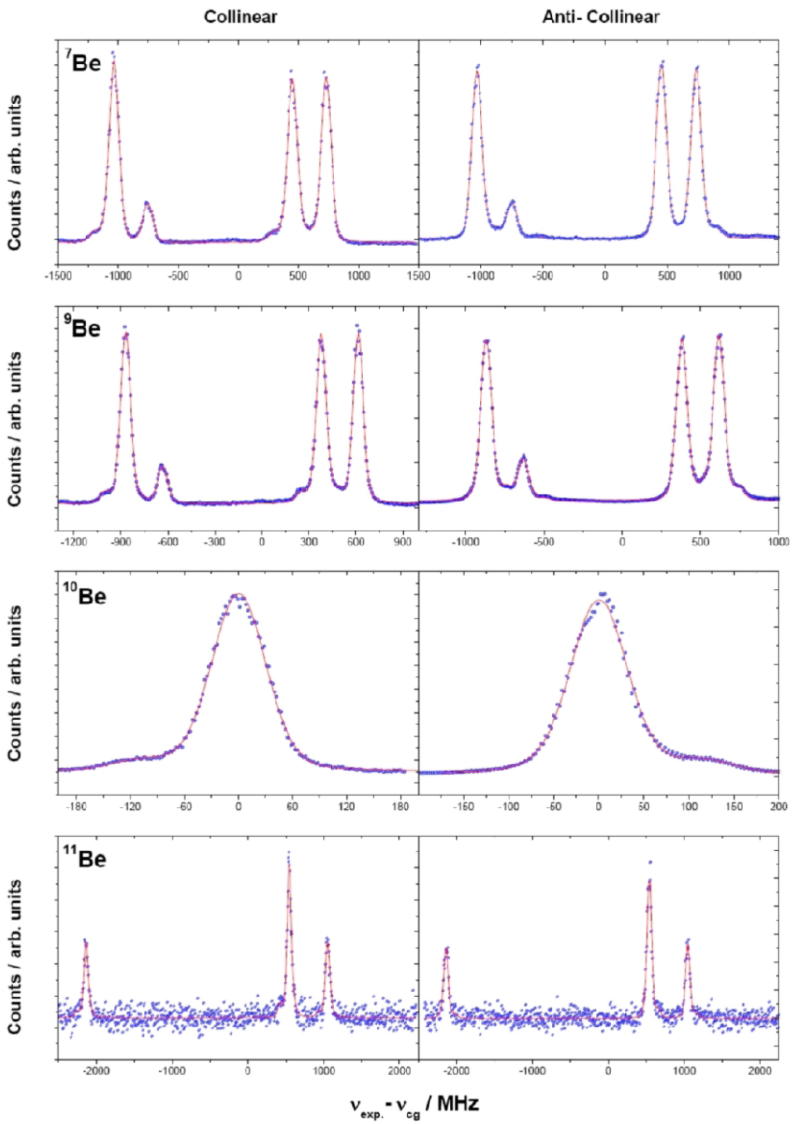
Experimental Setup



Collinear

Anticollinear

Results: Absolute Transition Frequencies



isotope	absolute frequency ν_0	$\Delta\nu_0$
Be	*GHz*	*MHz*
7	957150,31638	1,68
9	957199,55326	1,54
10	957216,87706	2,05
11	957231,11826	1,41

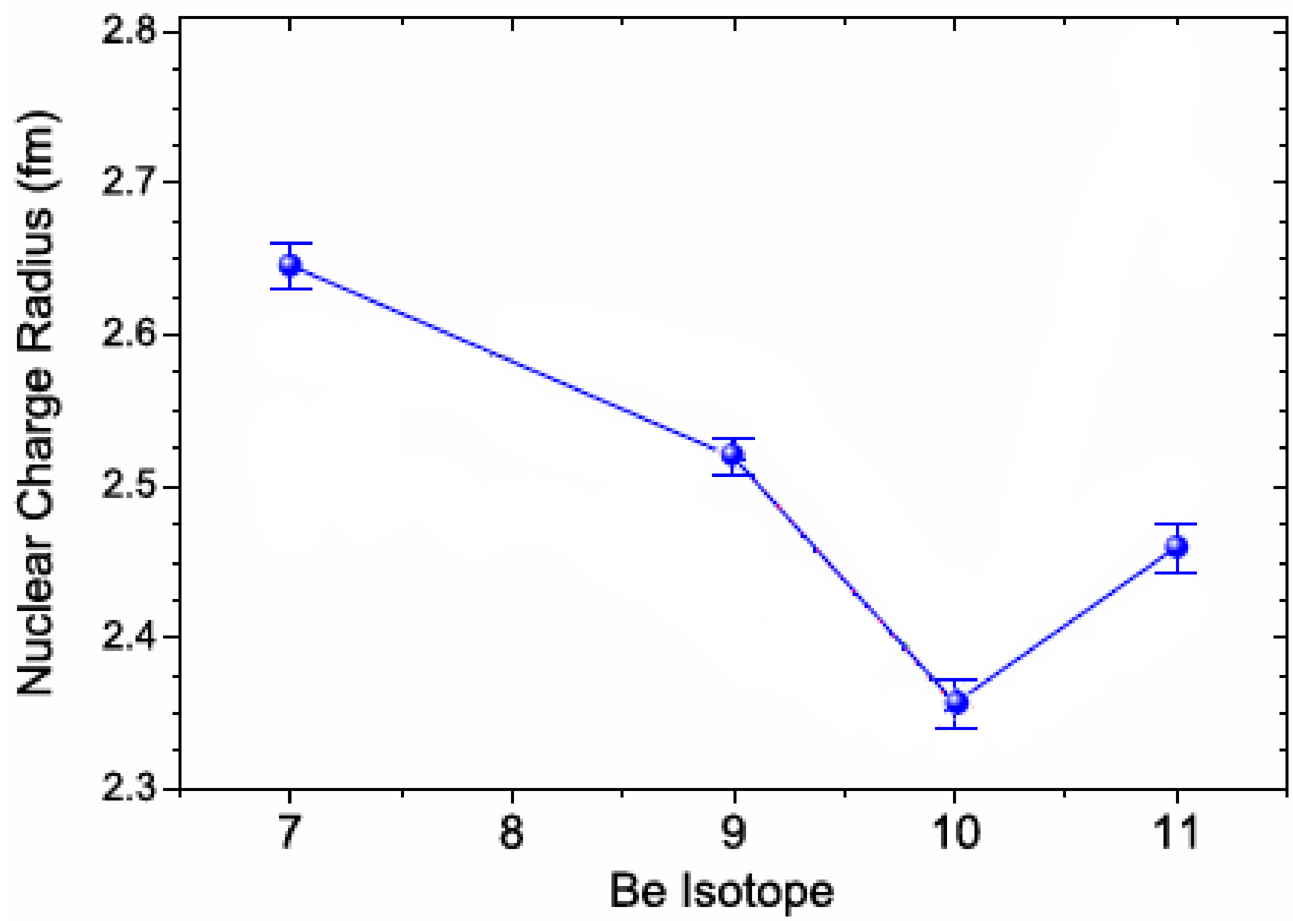
$\Delta\nu_0$ includes:

statistical standard deviation

+ laser-ion beam misalignment ~ 500 kHz
+ rubidium clock uncertainty ~ 580 kHz
+ ion recoil correction ~ 900 kHz

Beryllium: Nuclear Charge Radii

Electron Scattering: $r_c(^9Be)$ = 2.519(12) fm, J.A. Jansen et al., Nucl.Phys.A **188**, 337 (1972).
Muonic Atoms: $r_c(^9Be)$ = 2.39(17) fm, L.A. Schaller, Nucl.Phys.A **343**, 333 (1980).



● Experiment

W. Nörtershäuser *et al.*, PRL **102**, 062503 (2009).

References:

NCSM2005: No Core Shell Model
P. Navratil, PRC 73, 065801 (2006) (^{7}Be)
C. Forssen, Phys. Rev. C71 (2005) (^{9,11}Be)
P. Navratil, priv. comm. (2008) (^{10}Be)

Tanihata: Interaction Cross Sections with Glauber model
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Thanks to R.Torabi, Th. Neff, H. Feldmeier and P. Navratil for providing unpublished data !

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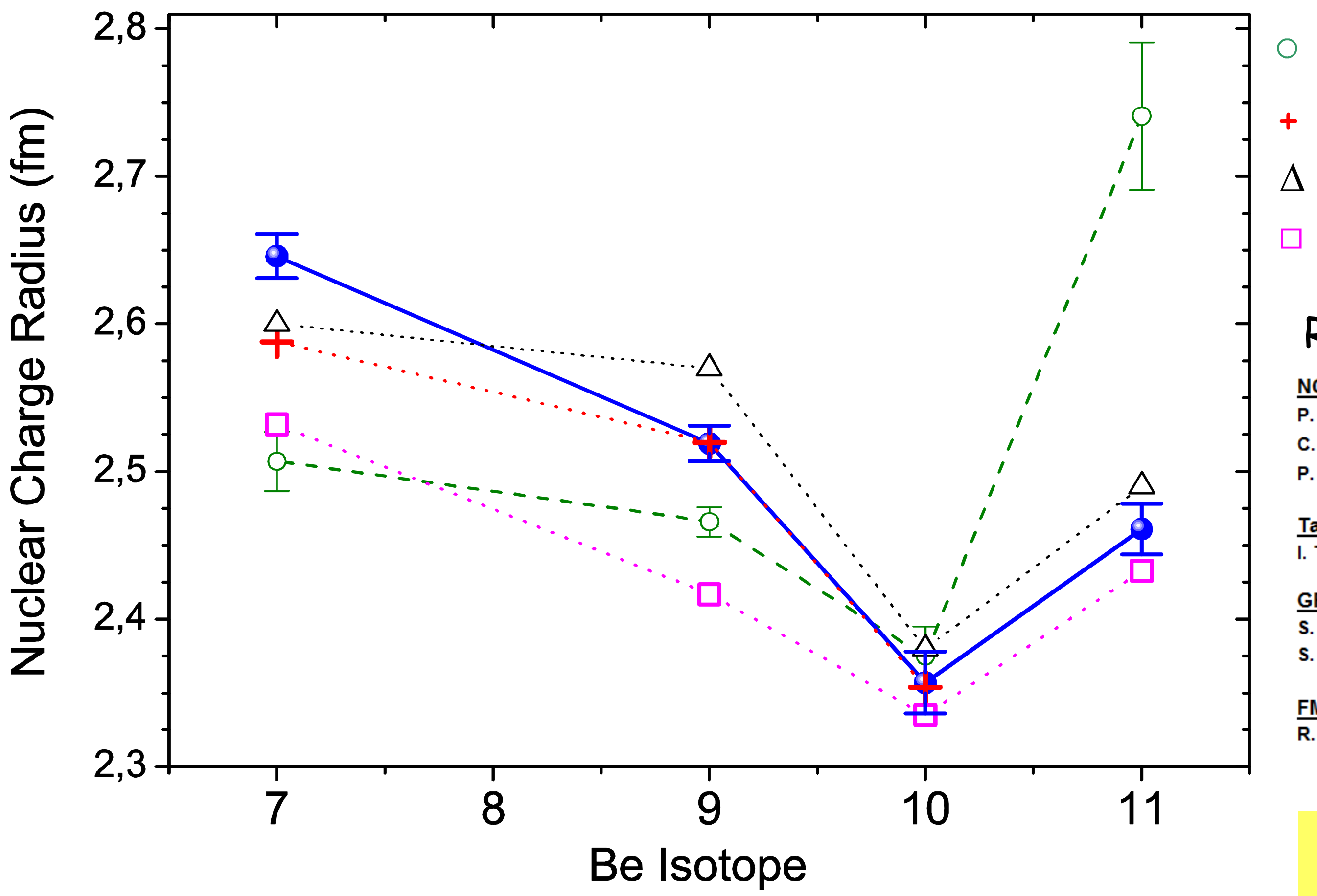

W. Nörtershäuser *et al.*, PRL **102**, 062503 (2009).

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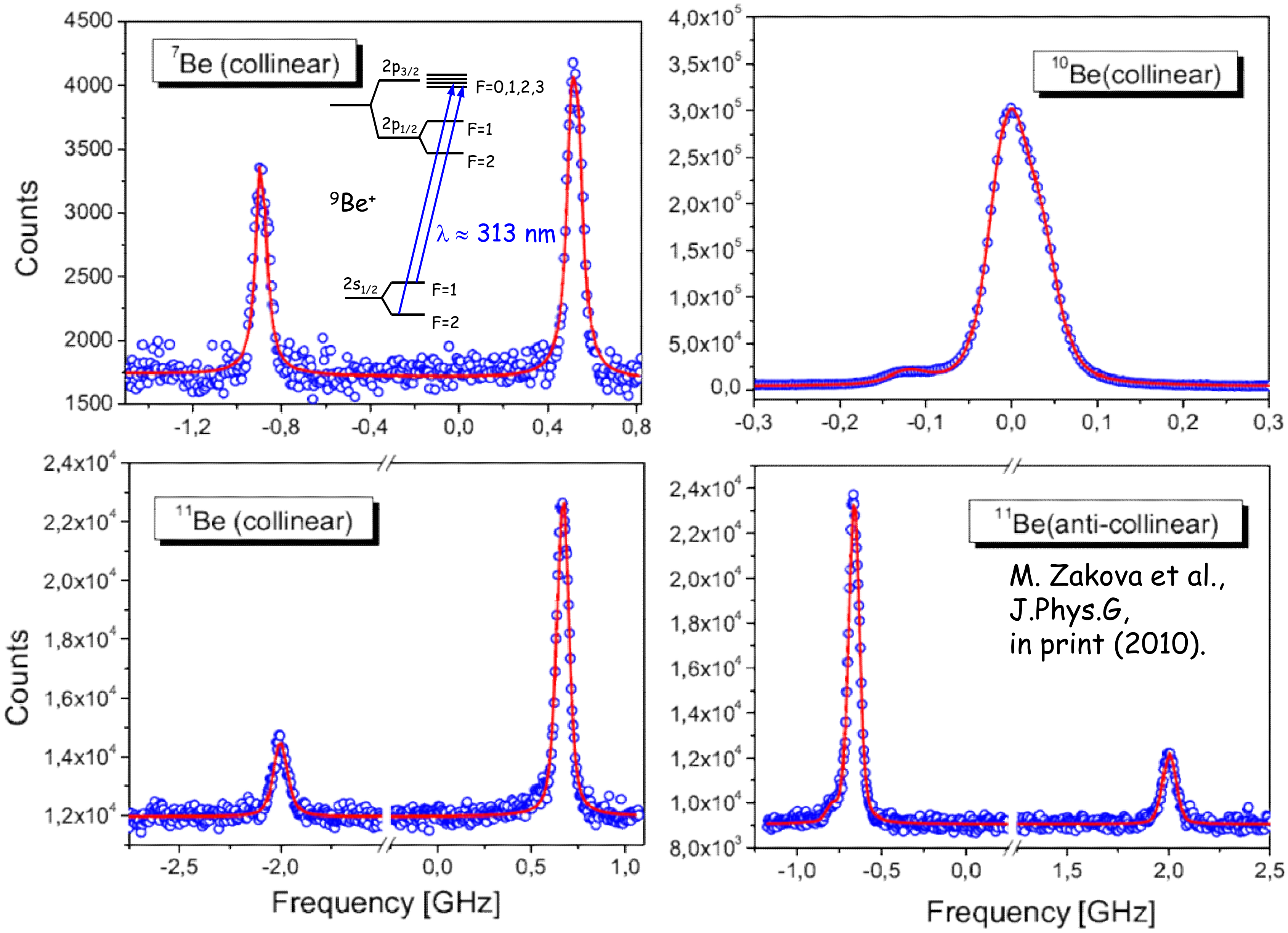
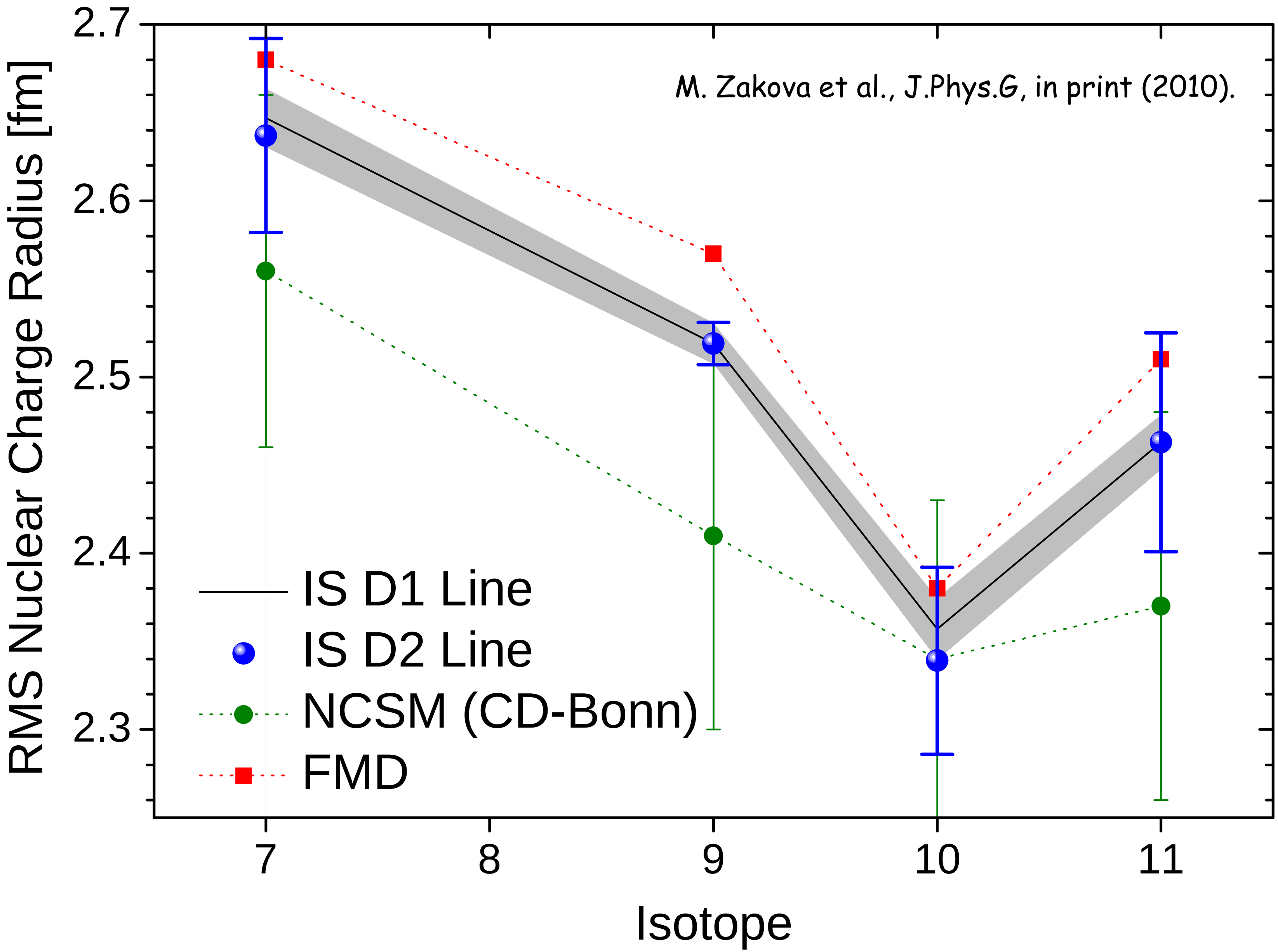
Beryllium Spectra in the D2 Transition



Charge Radii of Beryllium Isotopes

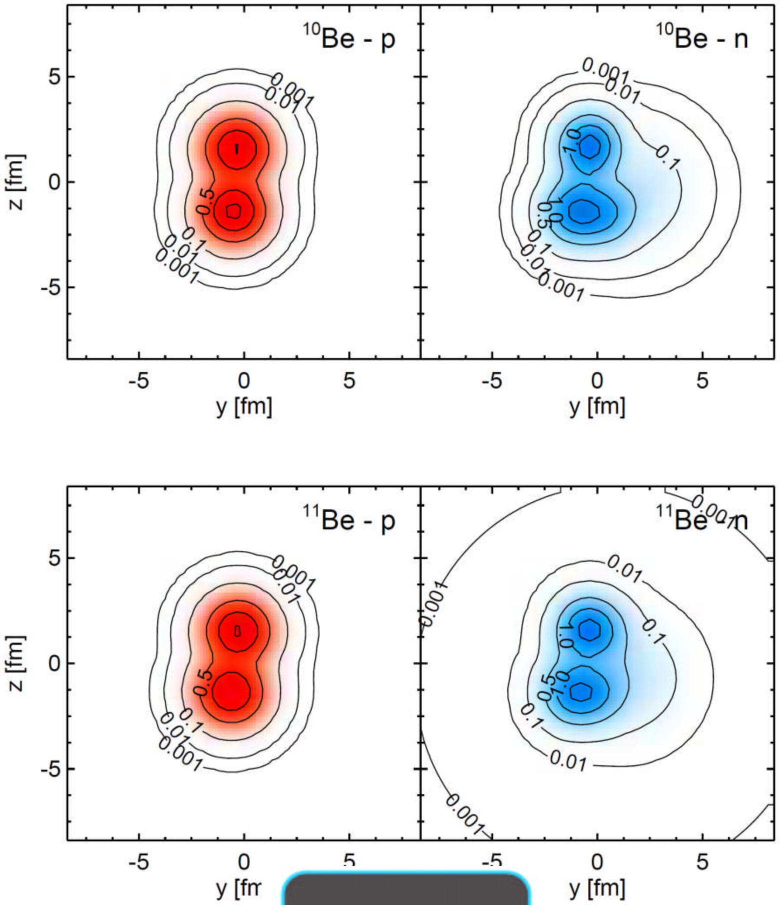


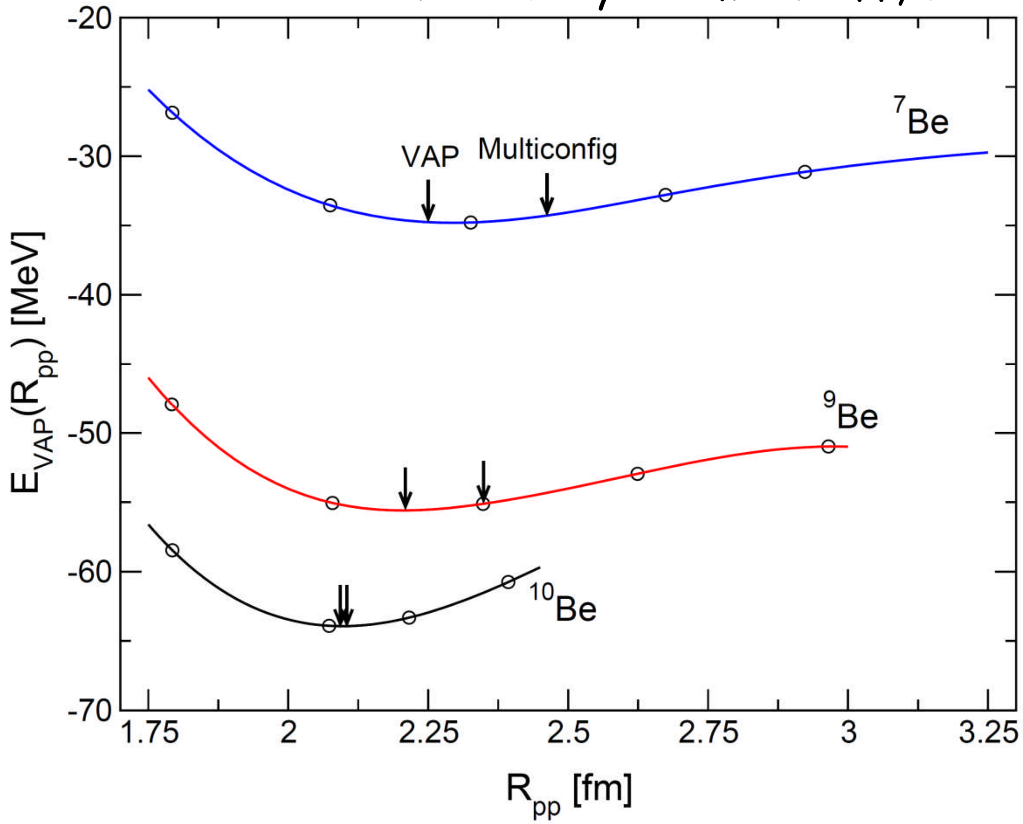
Berylium Charge Radii in FMD Calculations

FMD: Fermionic Molecular Dynamics

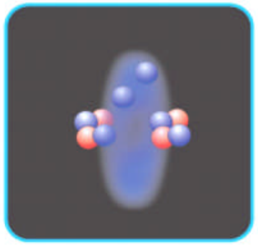
M. Zakova, Th. Neff et al., J.Phys.G, in print (2010).

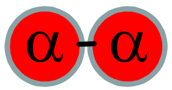
Calculations by Thomas Neff, GSI





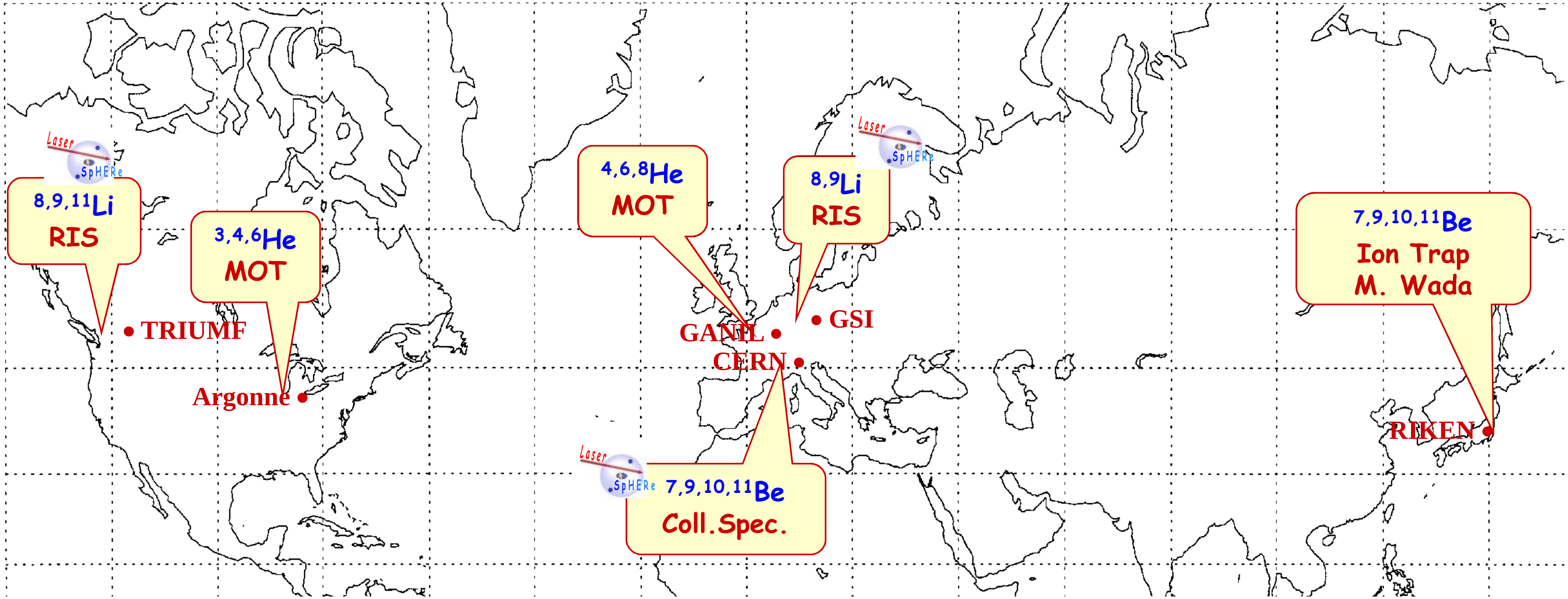
^{10}Be





R_{pp} = Charge radius with respect to the center-of-charge „α- α Distance“.

Summary



- High-Accuarcy Isotope Shift Measurements and Atomic Structure Calculations are an excellent Tool to Determine Nuclear Charge Radii.
- Currently this Technique is limited to Systems with up to three electrons.
- Charge Radii of Helium (^{3,4,6,8}He), Lithium (^{6,7,8,9,11}Li), and Beryllium Isotopes (^{7,9,10,11}Be) are measured.
- Theory should reproduce as many Observables as possible simultaneously.

Outlook / Open Questions

Absolute Charge Radii (Lithium, Beryllium)

- improved electron scattering data
- improved atomic structure calculations

Details of the Nuclear Structure:

- Wave Function
- Amount of Core Polarization

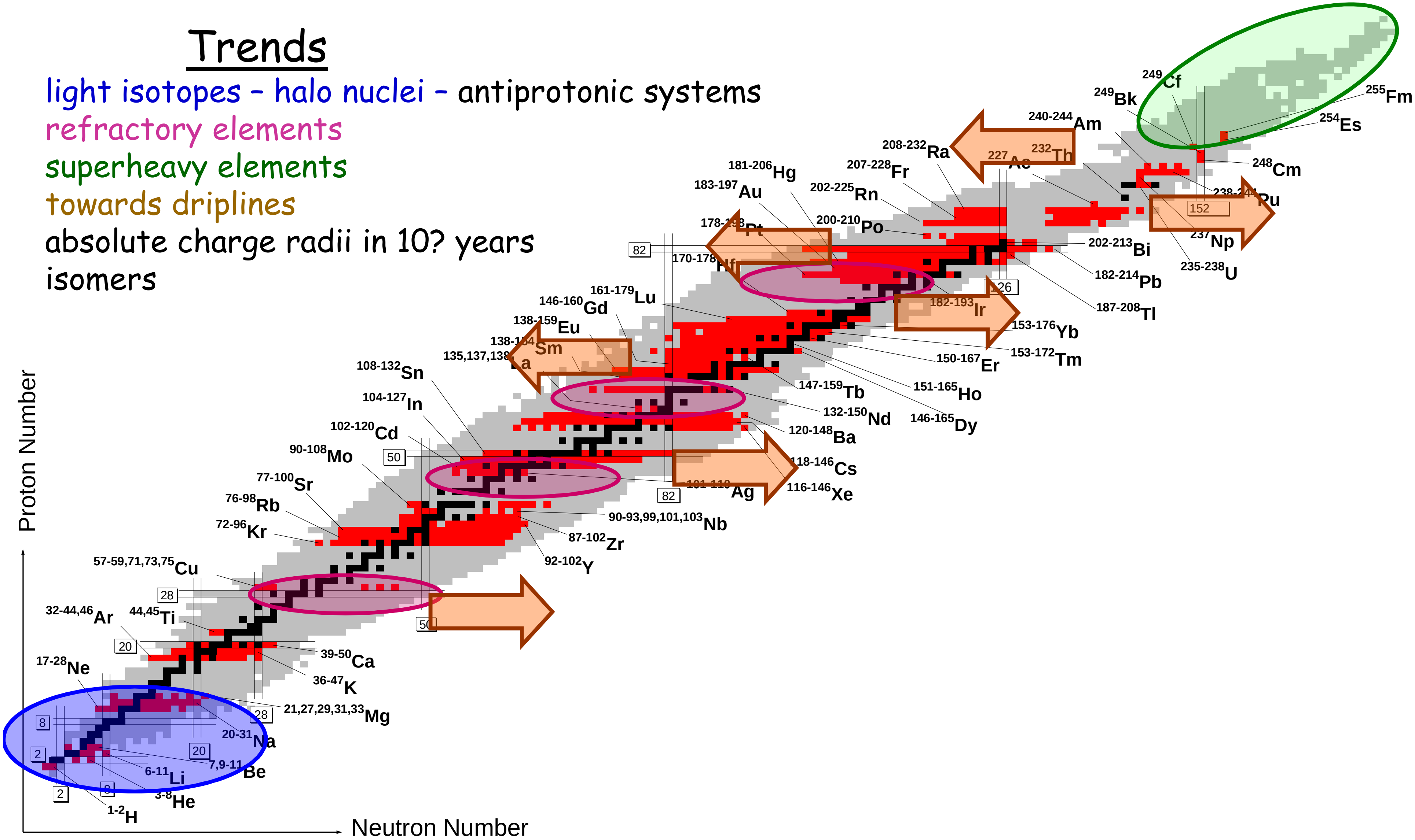
How to proceed for heavier (light) elements ?

Near Future: Measurement of ^{12}Be (~ 2000 Ions/s)

Trends and Developments

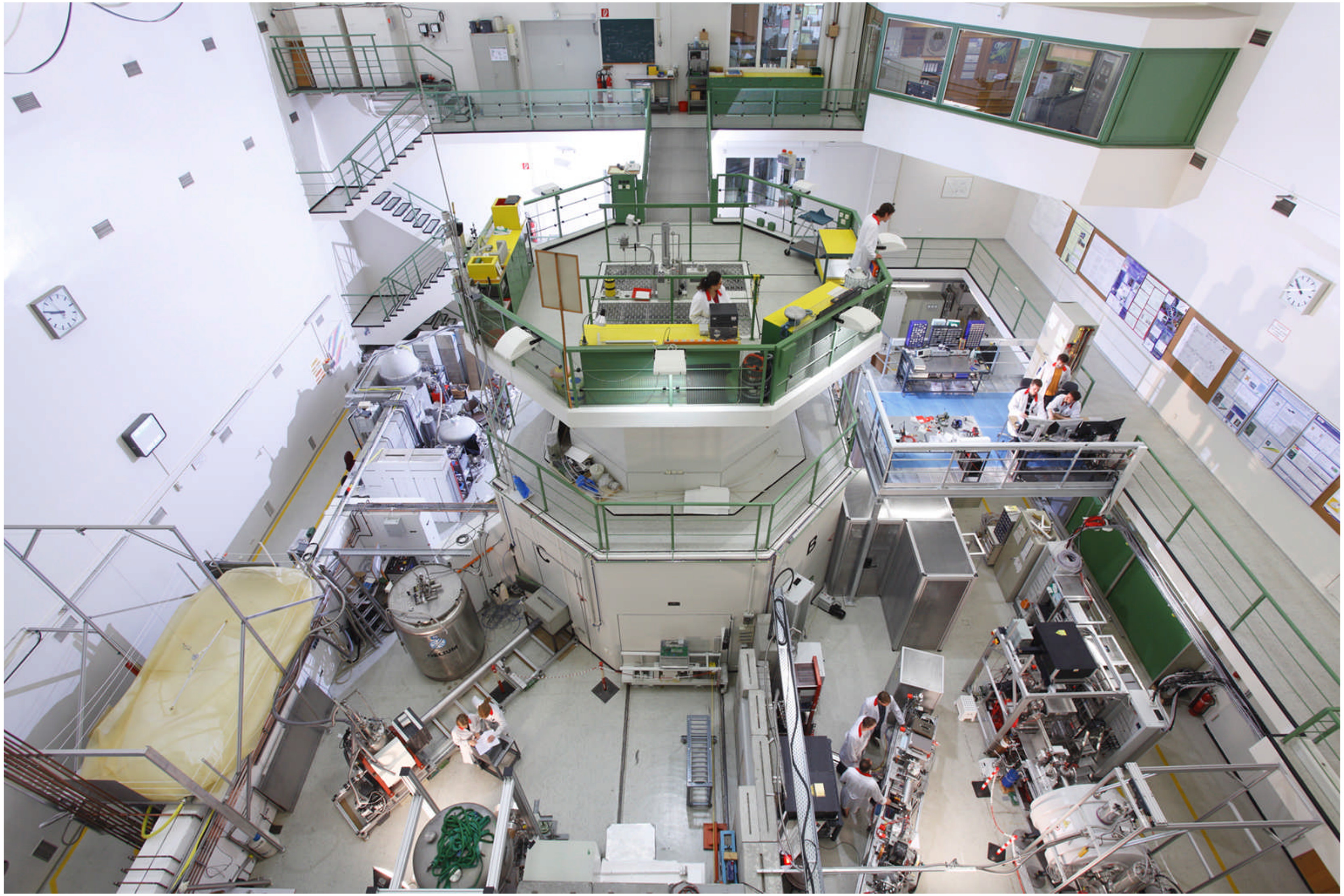
Trends

light isotopes – halo nuclei – antiprotonic systems
refractory elements
superheavy elements
towards driplines
absolute charge radii in 10? years
isomers



TRIGA-SPEC = TRIGA-TRAP + TRIGA-LASER

Prototyping MATS and LASPEC



Developments during the last years

The LASPEC Community (+ Friends) work continously to advance and improve laser spectroscopy, and gain new territory ...

Cooled and bunched beams

MOT Spectroscopy of Short-Lived Nuclei

State Preparation in a Cooler and Buncher

Frequency-Comb-Based Spectroscopy

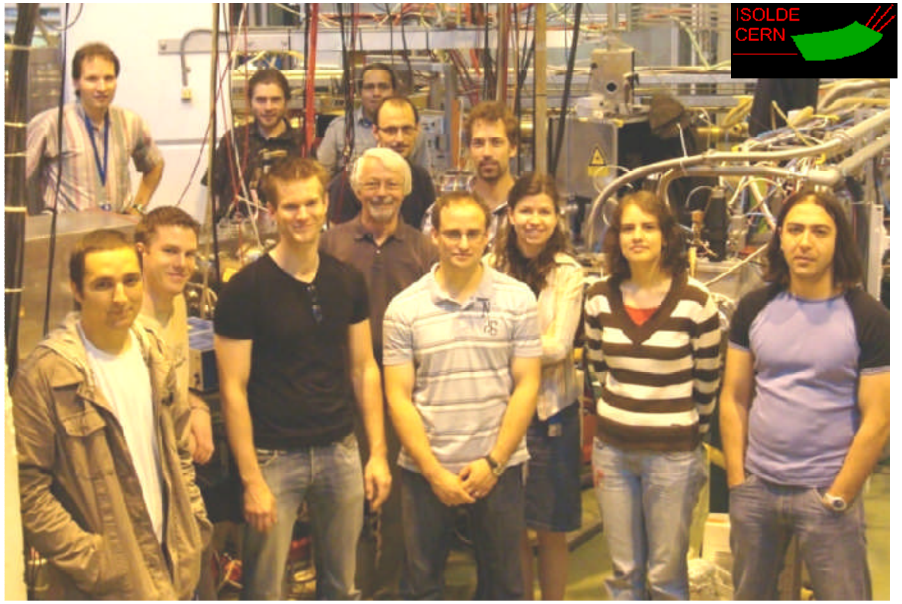
ß-Asymmetrie Detection for Isotope Shifts

Superheavy Element Spectroscopy with Pulsed RIMS

.....

JOHANNES GUTENBERG UNIVERSITÄT MAINZ GSI HELMHOLTZ GEMEINSCHAFT Institut für Kernchemie an der Universität Mainz

^{11}Li at ISAC, October 2004



^{11}Be at COLLAPS, June 2007

ToPLiS

D. Albers, B.A. Bushaw, J. Behr, P. Bricault, **A. Dax**, J. Dilling, M. Dombsky, G.W.F. Drake, **G. Ewald**, S. Götte, R. Kirchner, H.-J. Kluge, Th. Kühl, J. Lassen, P. Levi, M. Pearson, E. Prime, V. Ryjkov, **R. Sánchez**, **A. Wojtaszek**, Z.-C. Yan, C. Zimmermann

BeTINa

M. Zakova, **D. Tiedemann**,, Z.Andjelkovich, K. Blaum, M. Bissell, R. Cazan, G.W.F. Drake, **Ch. Geppert**, M. Kowalska, J. Krämer, **A. Krieger**, R. Neugart, **R. Sanchez**, B. F. Schmidt-Kaler, Z.-C. Yan, D. Yordanov, C. Zimmermann

Laser SpHERe

Laser Spectroscopy of Highly Charged Ions and Exotic Radioactive Nuclei
(VH-NG-148 Helmholtz Young Investigators Group)

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