SFB 1245 Meet & Greet:
Laser Spectroscopy in A01 and A03

Charge Radii and Nuclear Moments from Laser Spectroscopy

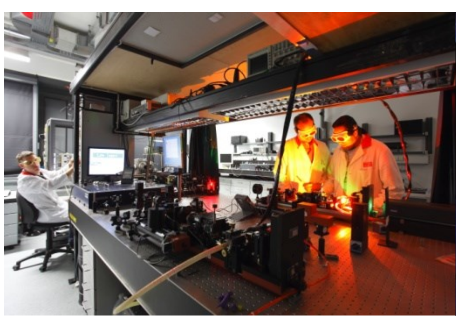
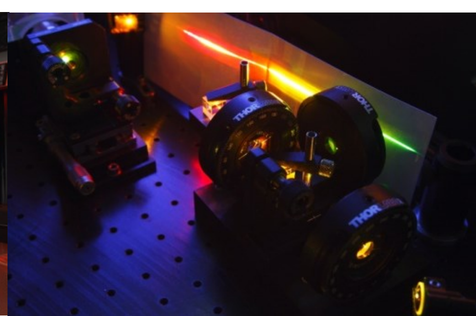
Wilfried Nörtershäuser

TECHNISCHE UNIVERSITÄT DARMSTADT

24.02.2016

From frequencies to nuclear moments
The principle of collinear laser spectroscopy
Collinear spectroscopy online: Where and why?
A01: Charge radius of ^{8}B
A03: Nuclear moments of Fe and Pd isotopes

Laser SpHERe
Laser Spectroscopy of Highly Charged Ions and Exotic Radioactive Nuclei

Nuclear Information from Laser Spectroscopy

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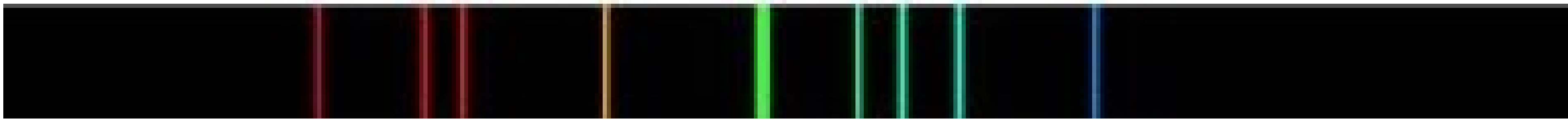
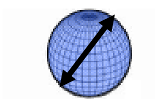
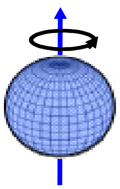


Nuclear Charge Radii

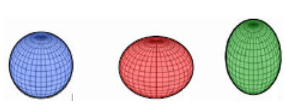


Nuclear Spin

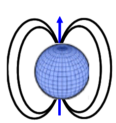


Ground State Properties of Exotic Nuclei

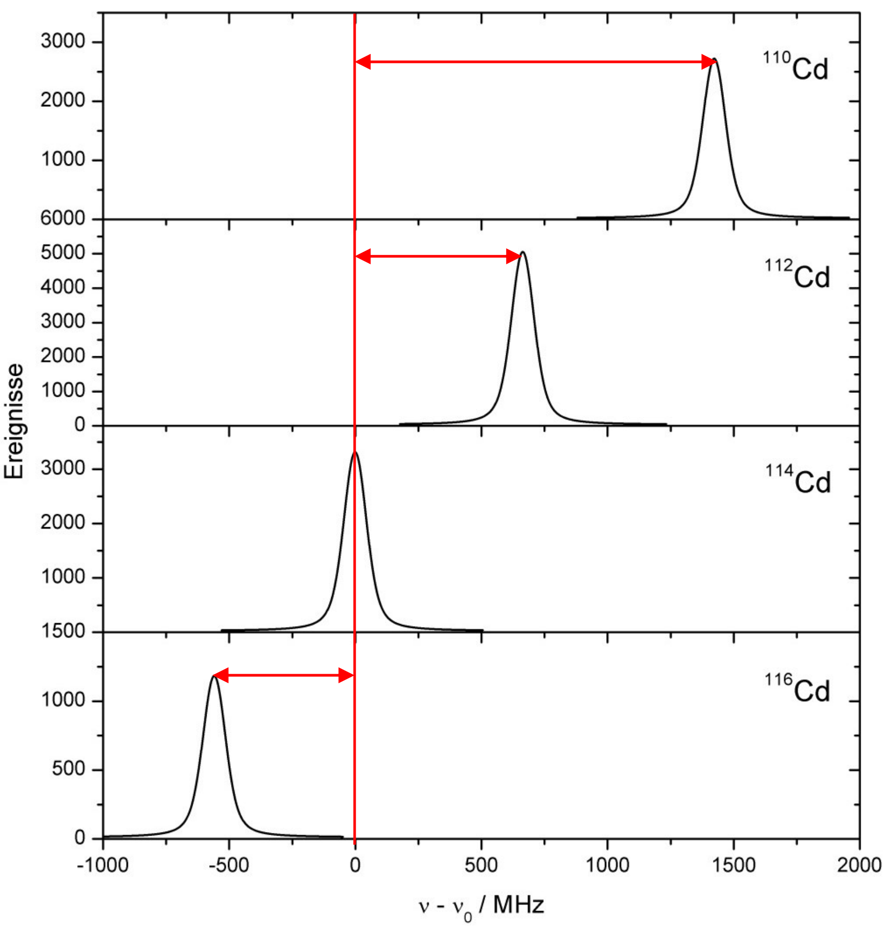
Electric Quadrupole Moment



Magnetic Moment

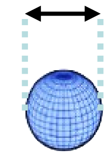


Isotope Shift



Isotope shift

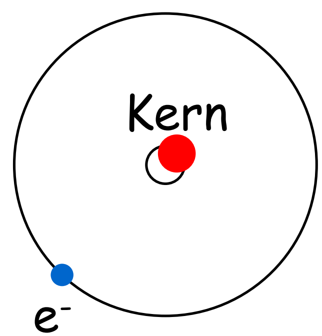
Charge radius

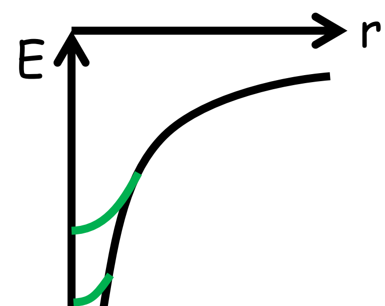


$$\delta_{IS}^{A,A'} = K \cdot \frac{M_{A'} - MA}{M_A M_{A'}} + F \cdot \delta\langle r^2\rangle^{A,A'}$$

Mass effect

Field effect





Hyperfine Structure

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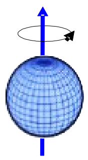
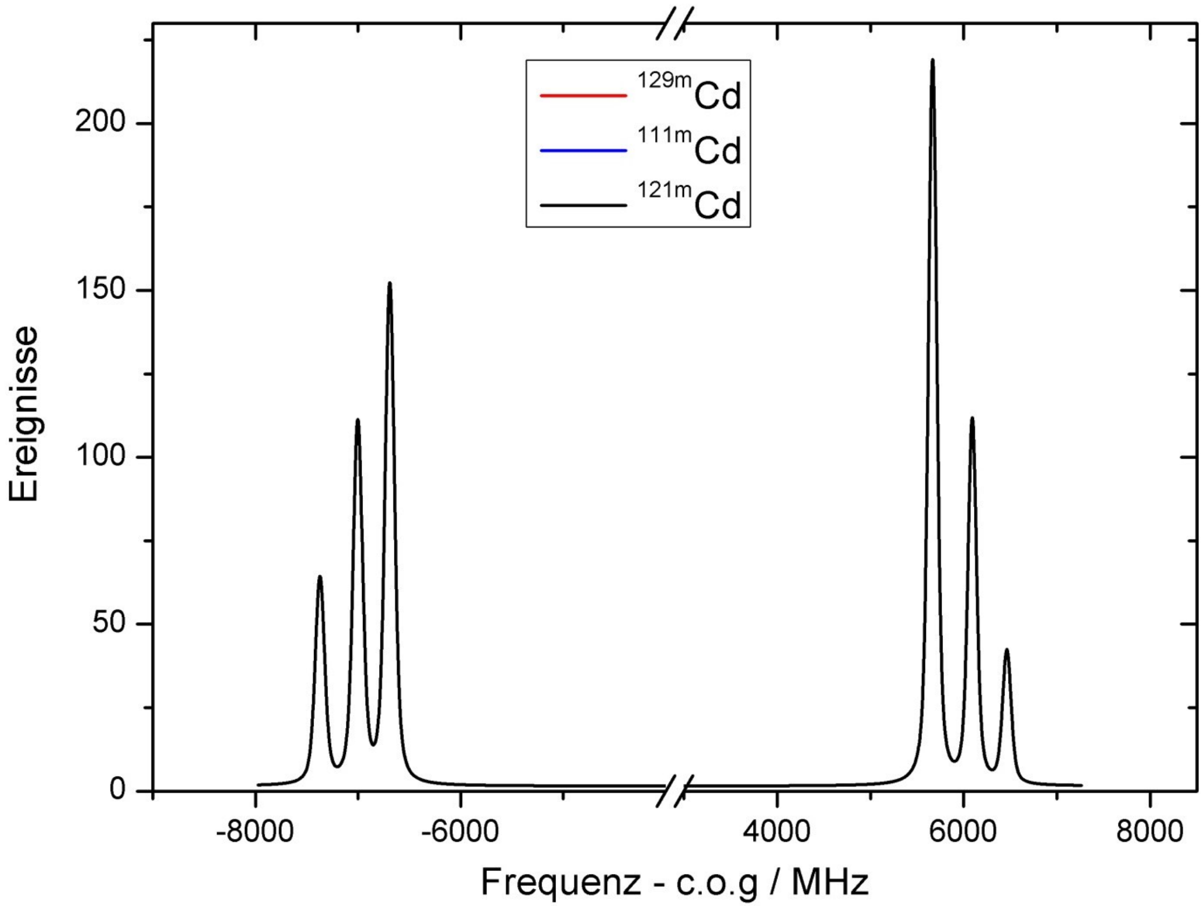
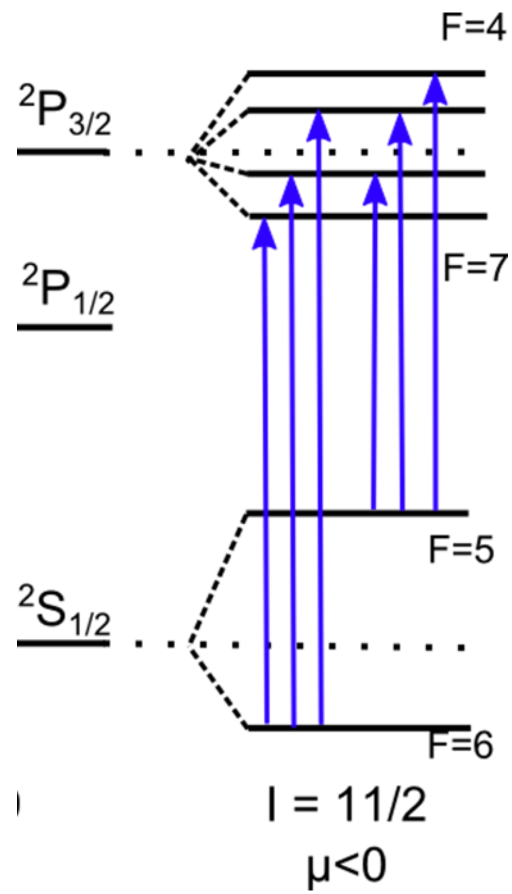
Spin

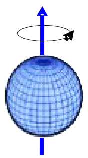




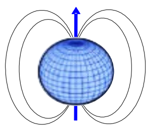


Hyperfine Structure

Spin

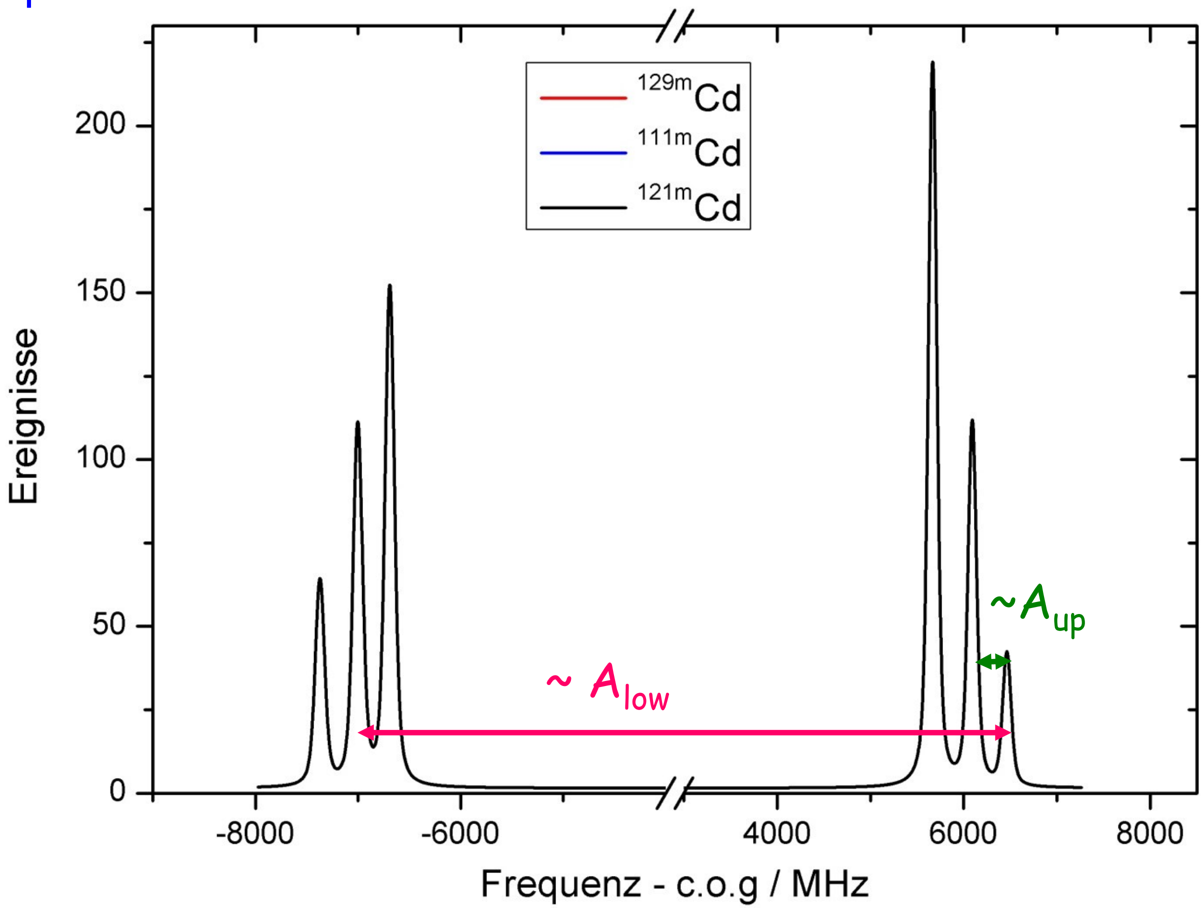


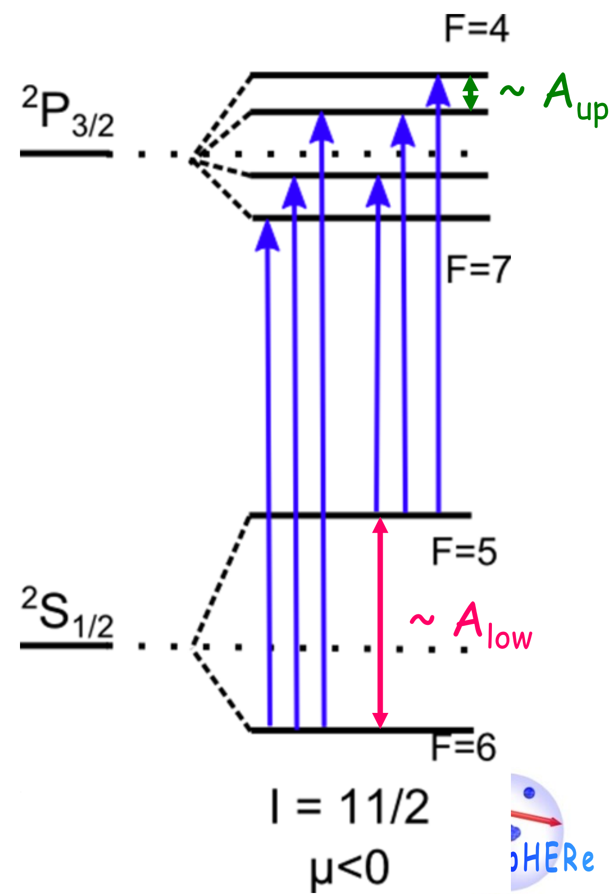
Magnetic Moment, μ_I



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

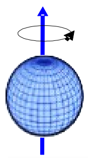
$$H_e(0) = \text{magnetic field at nuclear site}$$



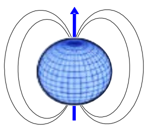


Hyperfine Structure

Spin



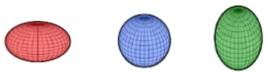
Magnetic Moment, μ_I



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

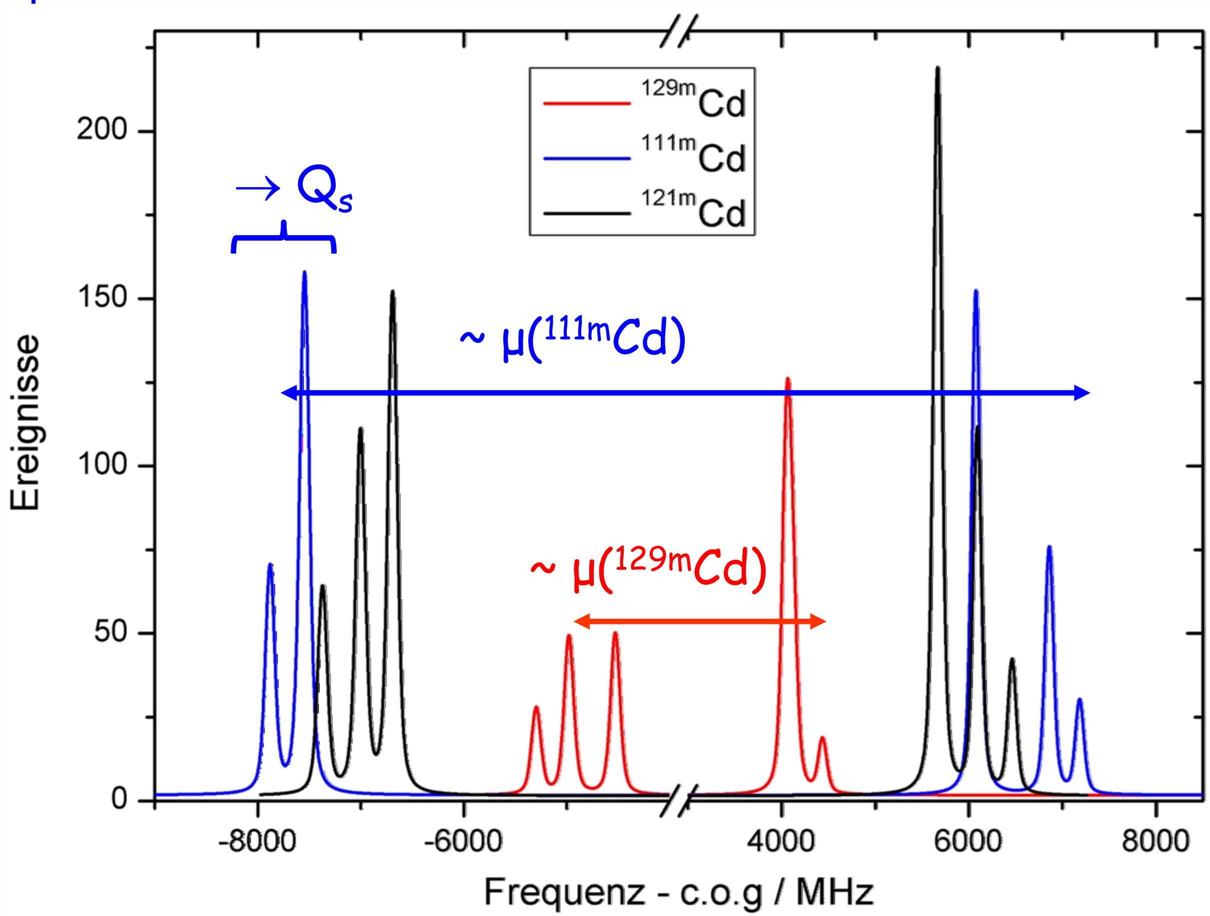
$H_e(0) =$ magnetic field at nuclear site

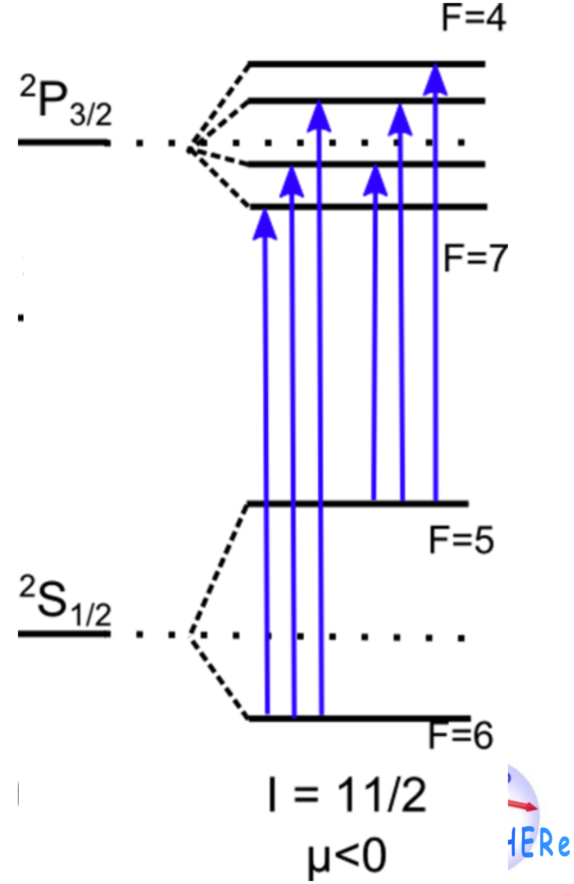
Spectroscopic quadrupole moment Q_s



$$B = eQ_s V_{zz}(0),$$

$V_{zz}(0) =$ electric field gradient at nuclear site





Evaluation of the Hyperfine Structure

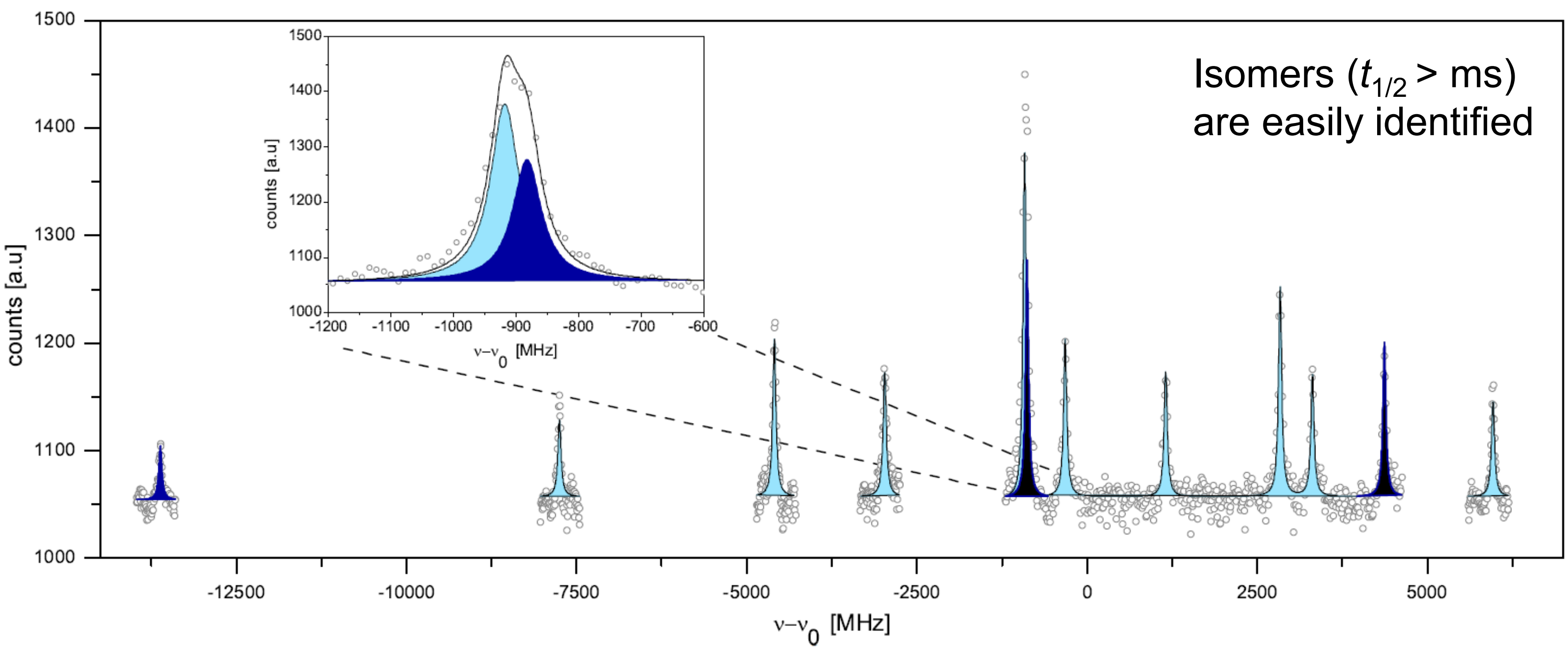
Peak Positions: $\nu = \nu_0 + \alpha_{\text{up}} A_{\text{up}} + \beta_{\text{up}} B_{\text{up}} - \alpha_{\text{low}} A_{\text{low}} - \beta_{\text{low}} B_{\text{low}}$

$$\alpha_{\text{up,low}}(I,J,F) = \frac{C}{2} = \frac{F(F+1) - I(I+1) - J(J+1)}{2} \qquad \beta_{\text{up,low}}(I,J,F) = \frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I \cdot J}$$

choose I, Nonlinear Least Squares Fitting $\Rightarrow A_u, A_l, B_u, B_l, \nu_0, \chi^2_{\text{red}}$

Isomer-Shift:

Isomer-Spin: $I^{\,m}$ $\qquad \nu^m = \nu^m_{\text{IS}} + \alpha^m_{\text{up}} A^m_{\text{up}} + \beta^m_{\text{up}} B^m_{\text{up}} - \alpha^m_{\text{low}} A^m_{\text{low}} - \beta^m_{\text{low}} B^m_{\text{low}}$ $\qquad \delta\nu_{\text{Isomer}} = \nu_{\text{IS}} - \nu^m_{\text{IS}}$



Origin of Collinear Laser Spectroscopy

Volume 17, number 3 OPTICS COMMUNICATIONS

HIGH-RESOLUTION LASER SPECTROSCOPY IN FAST BEAMS

S.L. KAUFMAN

Institut für Physik, Johannes Gutenberg-Universität,
D-6500 Mainz, Fed. Rep. of Germany

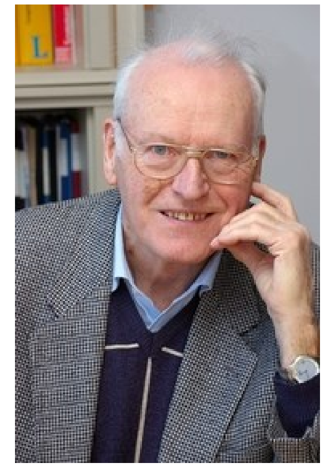
Received 3 March

Collinear Laser Spectroscopy on Fast Atomic Beams

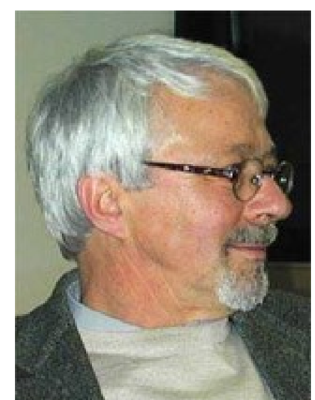
K.-R. Anton, S. L. Kaufman,[a] W. Klempt, G. Moruzzi,[b] R. Neugart,
E.-W. Otten, and B. Schinzler
Institut für Physik, Johannes Gutenberg–Universität, D-6500 Mainz, Federal Republic of Germany
(Received 1 August

In collinear geometry we have observed laser-excited, narrow resonances in fast beams of Na and Cs atoms obtained from ion beams by charge transfer collisions. Being

1980 First results at ISOLDE/CERN → COLLAPS

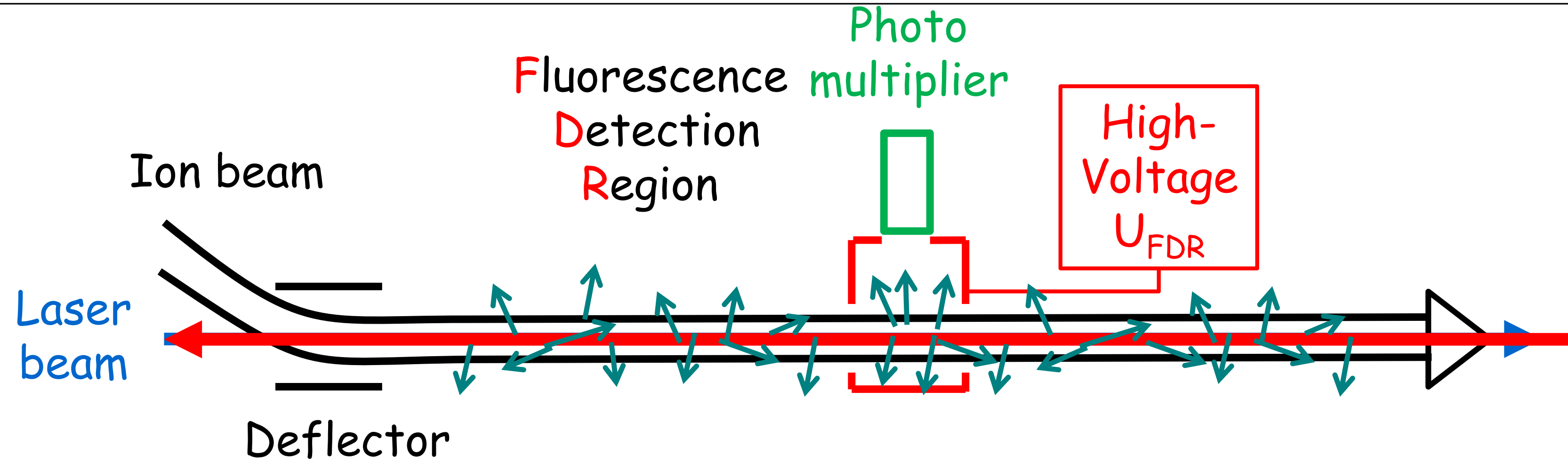


E.-W. Otten



R. Neugart

The Principle of Collinear Spectrosocpy



$$\beta = \upsilon / c$$

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

Collinear Doppler shift: $\nu_{\text{ion}} = \nu_{\text{laser}} \cdot \gamma \cdot (1-\beta)$

Anticollinear Doppler shift: $\nu_{\text{ion}} = \nu_{\text{laser}} \cdot \gamma \cdot (1+\beta)$

Resonance condition: $\nu_{\text{ion}} = \nu_0$

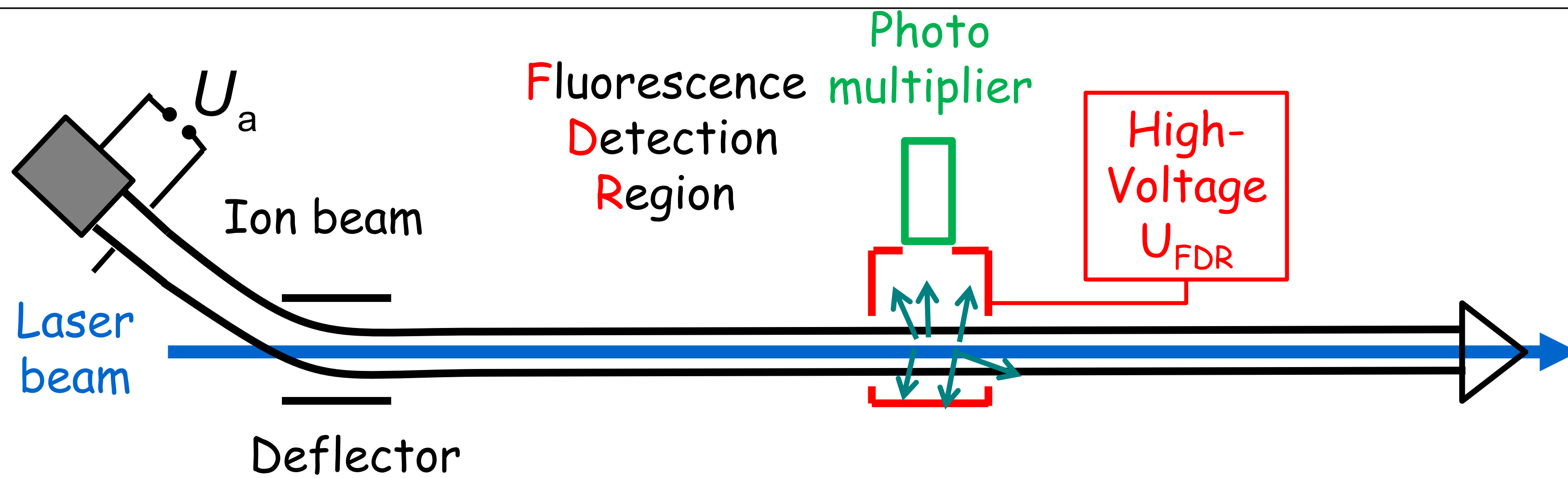
<u>Doppler-Tuning:</u>

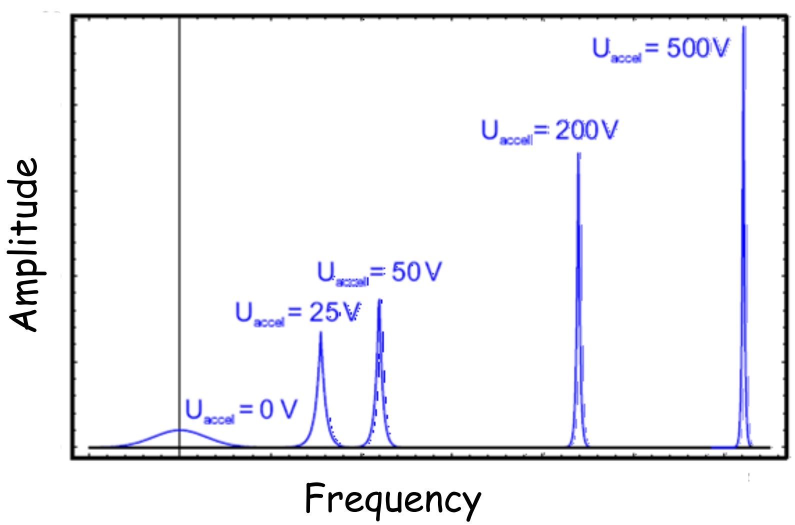
$\beta = \beta(U,m)$

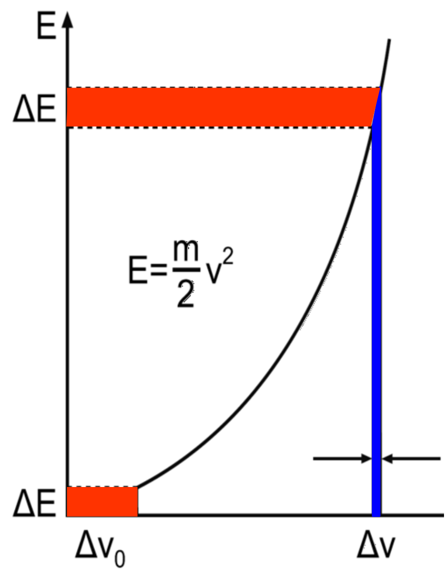
$$\Delta\nu_{\text{ion}} = \frac{\partial \nu_{\text{ion}}}{\partial U}\Delta U$$

$$\frac{\partial \nu_{\text{ion}}}{\partial U} = \frac{e\nu_0}{\sqrt{2eUMc^2}}$$

The Principle of Collinear Spectrosocpy







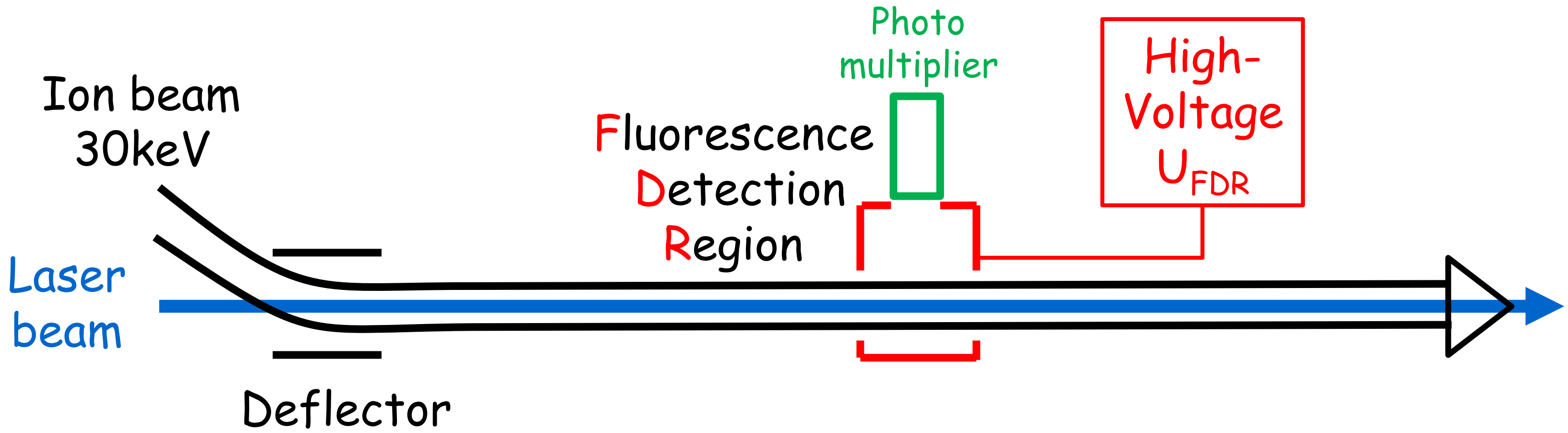
$$E = eU_a = 1/2\, m\upsilon^2$$

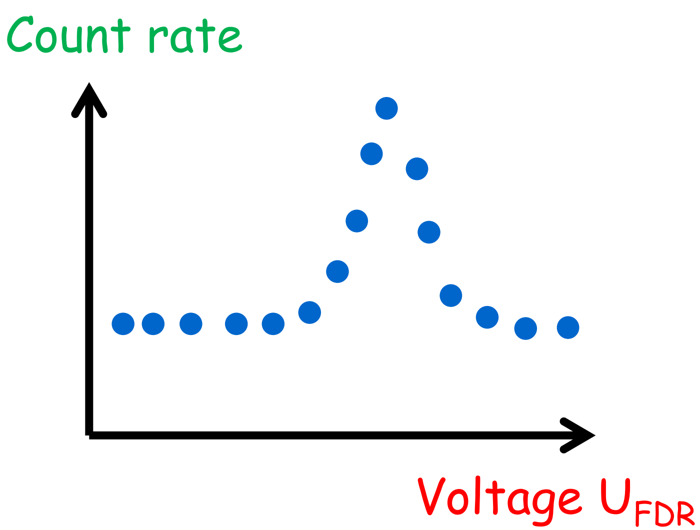
$$\delta E = m\upsilon\, \delta\upsilon$$

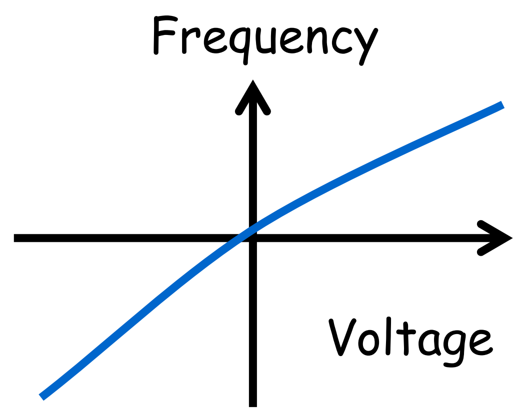
$$\delta\nu_{\text{Doppler}} = \nu_0\, \delta\upsilon / c$$

$$= \nu_0 \frac{\delta E}{\sqrt{2eU_a mc^2}}$$

Data Taking in Collinear Spectrosocpy

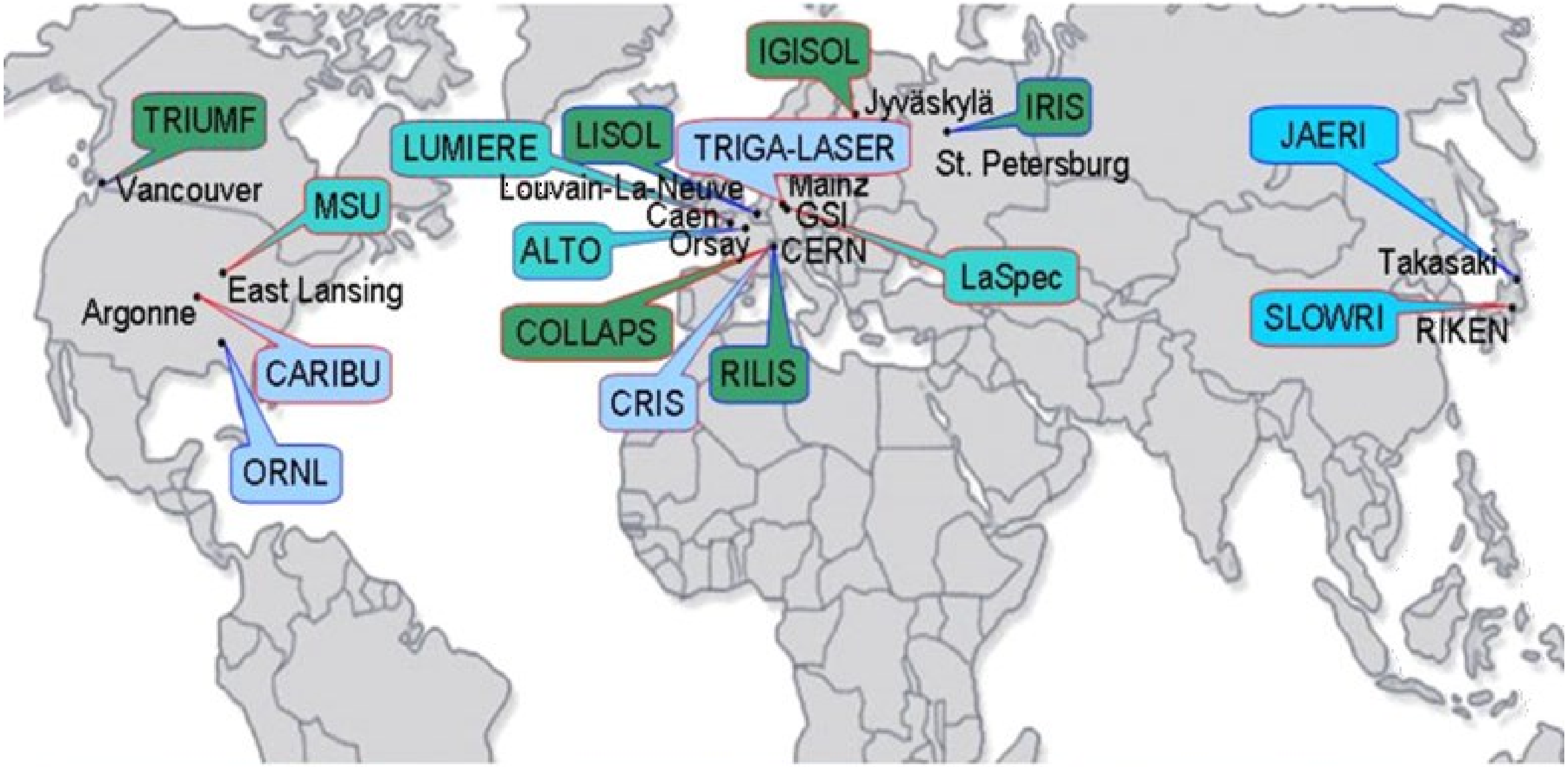






- universal
- fast
- sensitive
- high resolution

Collinear Spectroscopy at On-Line Facilities



operating facilities

facilities under construction ot test

planned facilities

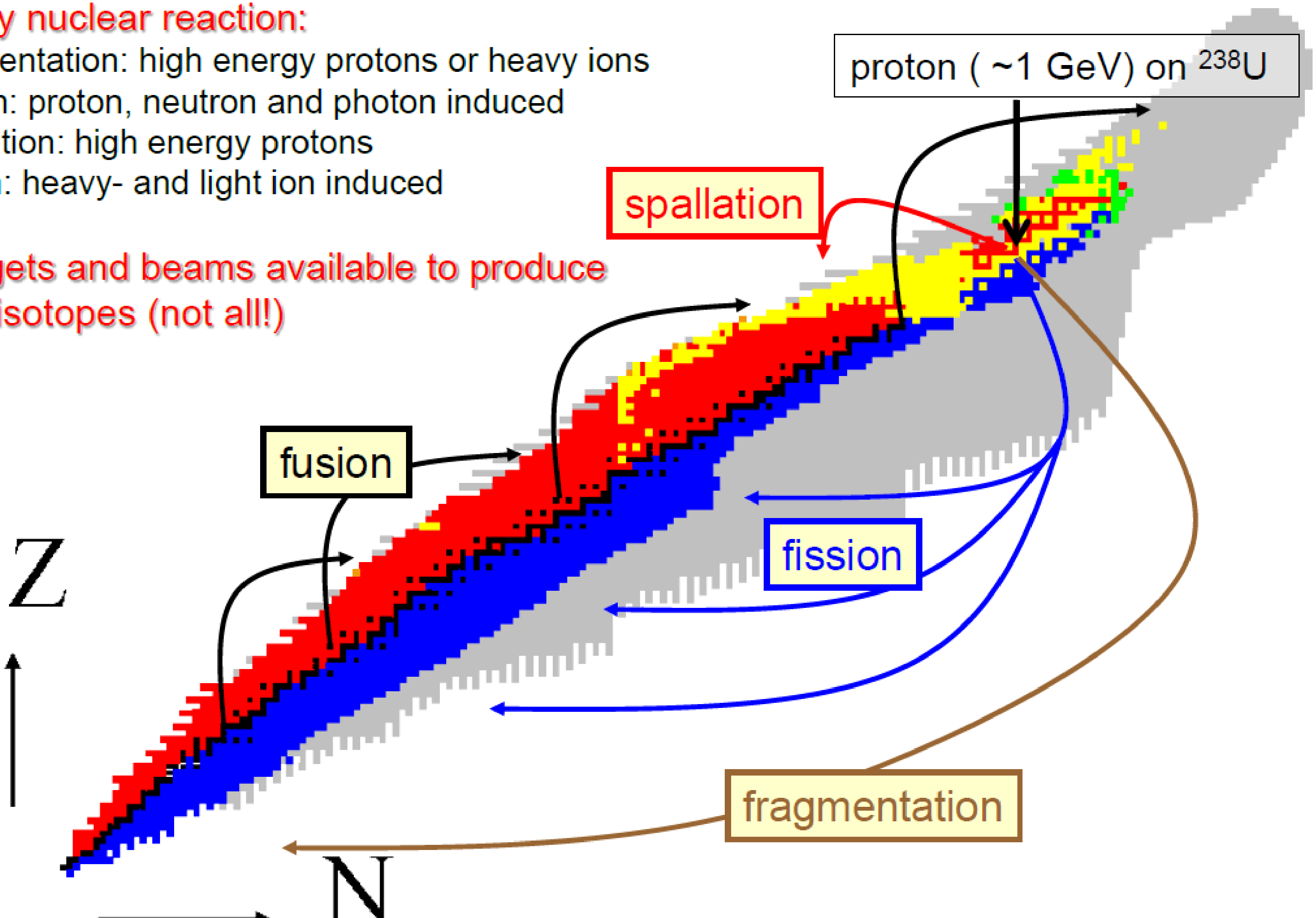
collinear laser spectroscopy

laser ion source

Reactions for Radioisotope Production

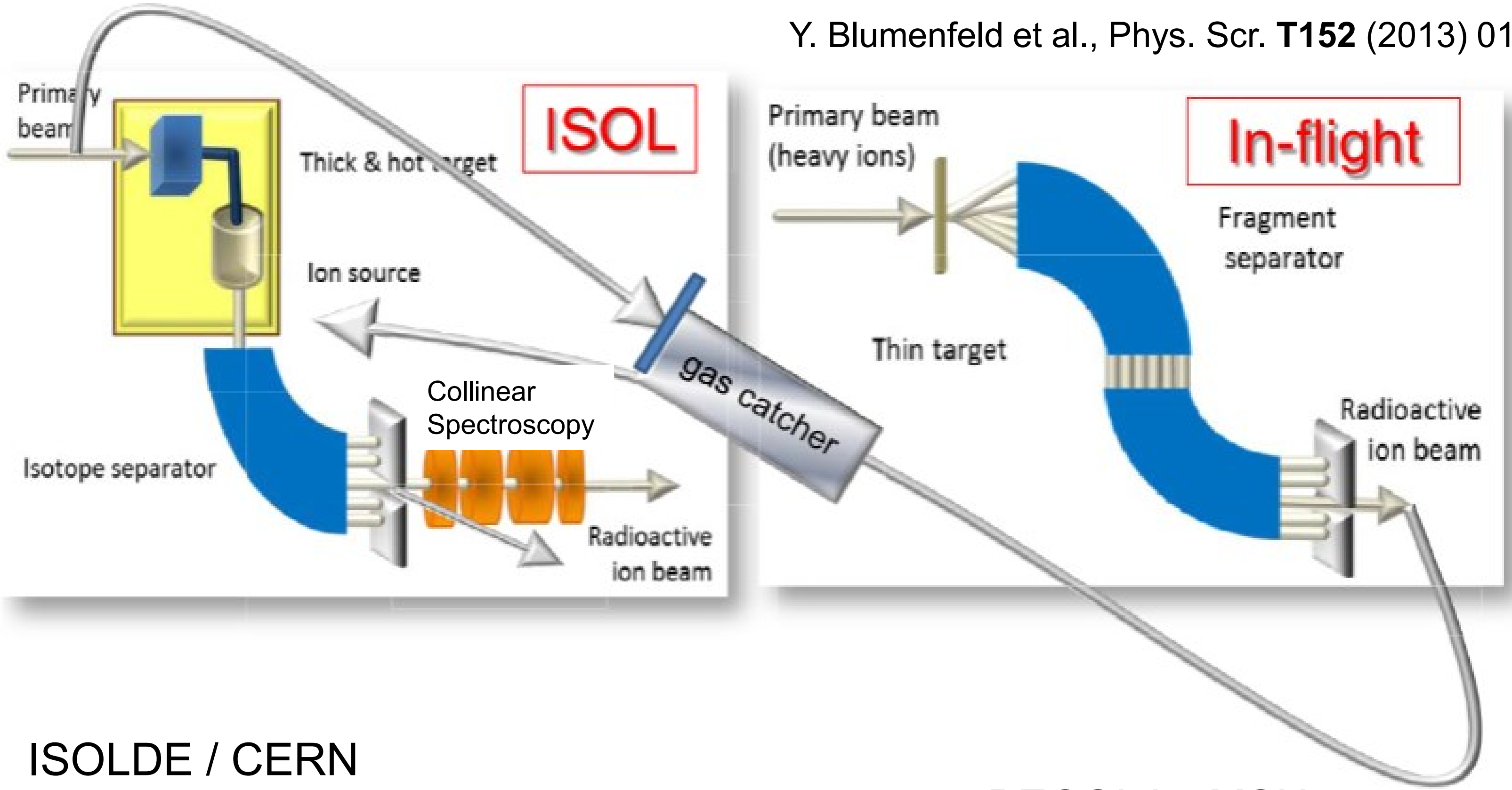
- Primary nuclear reaction:
  - fragmentation: high energy protons or heavy ions
  - fission: proton, neutron and photon induced
  - spallation: high energy protons
  - fusion: heavy- and light ion induced

⇒ targets and beams available to produce many isotopes (not all!)



Production Techniques

Y. Blumenfeld et al., Phys. Scr. **T152** (2013) 014023



ISOLDE / CERN
TRIUMF, Vancouver
SPIRAL2 / GANIL

IGISOL Jyväskylä
CARIBU Argonne
TRIGA-SPEC Mainz

BECOLA - MSU
ATLAS Argonne
FRIB - Riken

Radionuclides available at ISOLDE

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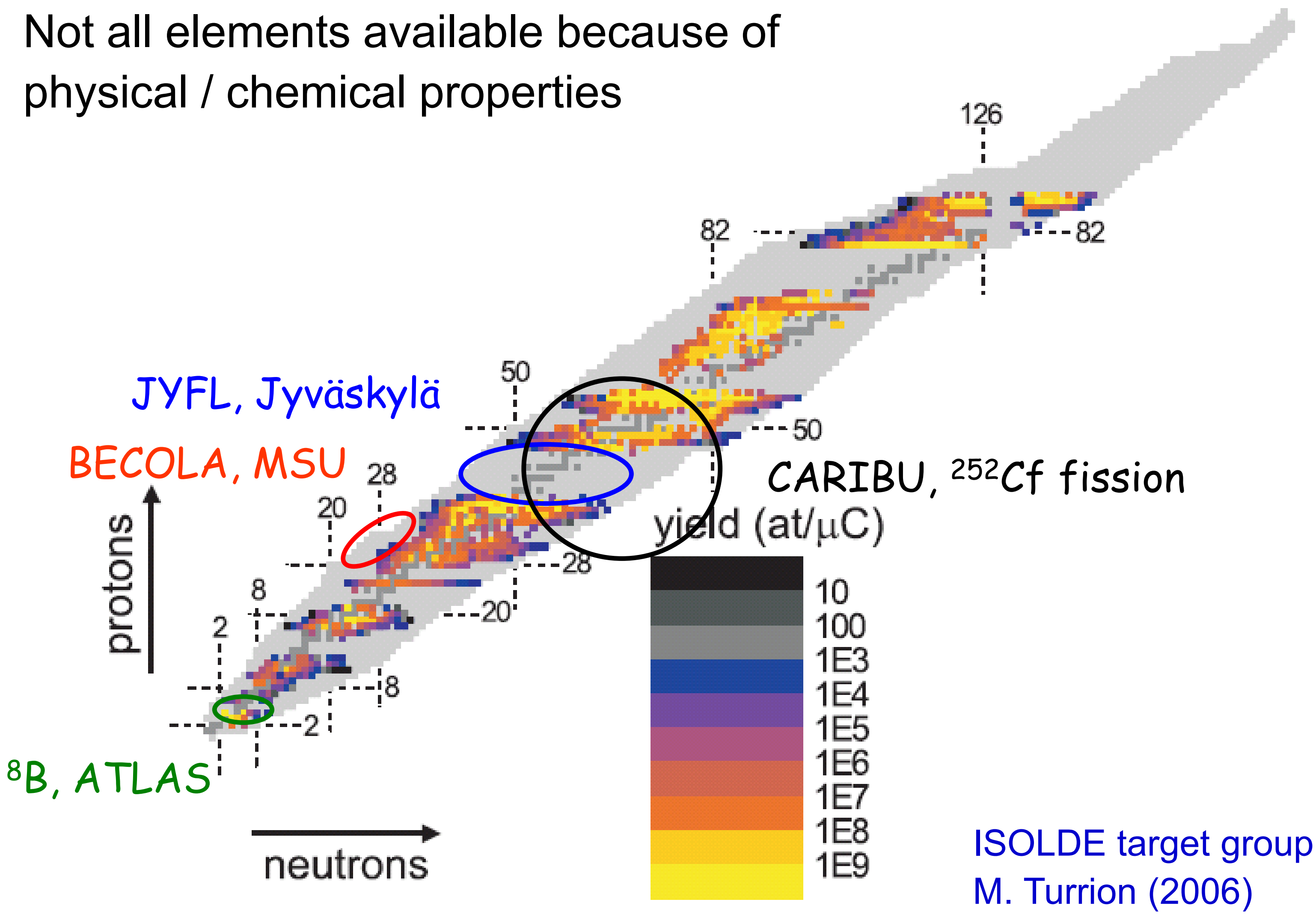
Not all elements available because of physical / chemical properties



ISOLDE target group
M. Turrion (2006)

Recent Laser Spectroscopic Work on Ground State Properties

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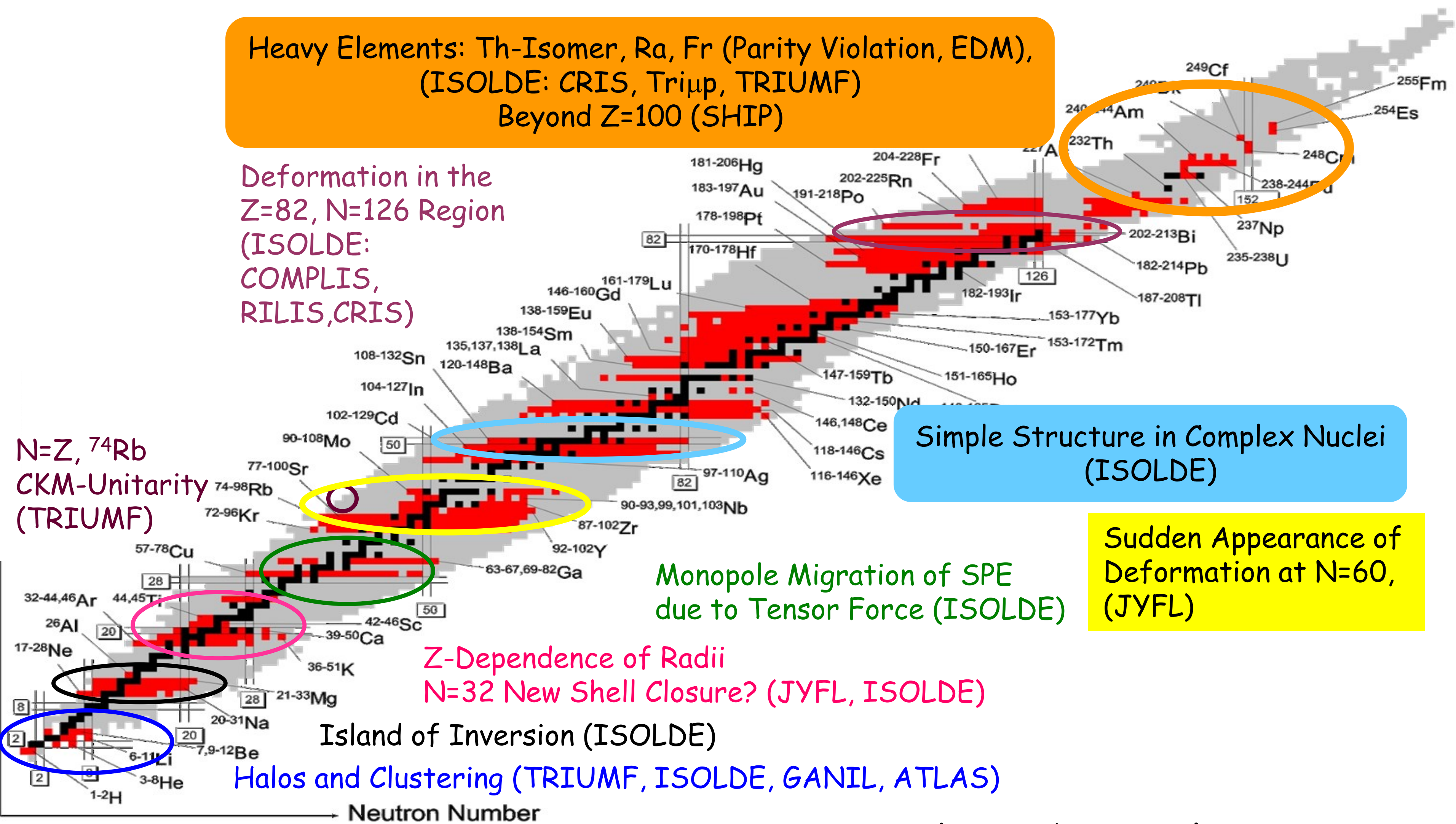

Heavy Elements: Th-Isomer, Ra, Fr (Parity Violation, EDM),
(ISOLDE: CRIS, Triμp, TRIUMF)
Beyond Z=100 (SHIP)

Deformation in the Z=82, N=126 Region (ISOLDE: COMPLIS, RILIS,CRIS)

N=Z, ^{74}Rb
CKM-Unitarity
(TRIUMF)

Simple Structure in Complex Nuclei (ISOLDE)

Sudden Appearance of Deformation at N=60, (JYFL)

Monopole Migration of SPE due to Tensor Force (ISOLDE)

Z-Dependence of Radii
N=32 New Shell Closure? (JYFL, ISOLDE)

Island of Inversion (ISOLDE)

Halos and Clustering (TRIUMF, ISOLDE, GANIL, ATLAS)

K. Blaum, J. Dilling and W. Nörtershäuser, Phys. Scr. T152, 014017 (2013)

might not be complete …

Recent Example

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TU | Die Universität | Vorbeischauen | Studieren | Gemeinsam forschen | Karriere planen | Verbunden bleiben

Suche »

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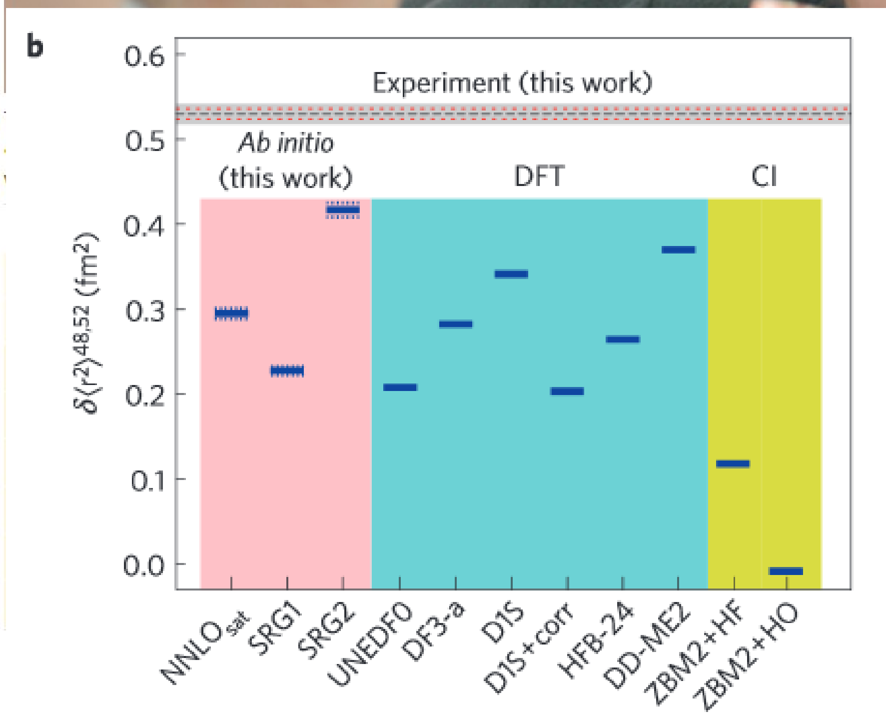
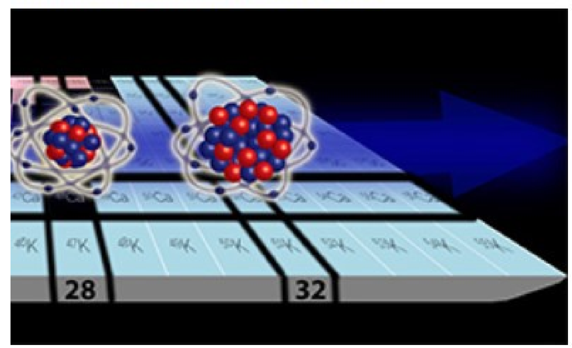


09.02.2016

…alcium-Atomkerne entdeckt



…isotope. Die „doppelt magischen" Isotope mit den Massenzahlen …ungsradien. Die erstmalige Messung des Isotops Ca-52 ergab …: COLLAPS Collaboration / Ronald Fernando Garcia Ruiz

…er noch für eine Überraschung gut: Nachdem erst vor kurzem die Isotope mit den Massenzahlen 52 (Ca-52) und 54 (Ca-54) als weitere „magische" und damit relativ stabile Kerne in der Isotopenreihe etabliert wurden, passen die Ergebnisse jüngster laserspektroskopischer Untersuchungen an Ca-52 nicht recht in dieses

Kontakt

Technische Universität Darmstadt
Kommunikation und Medien
S1|01 517
Karolinenplatz 5
64289 Darmstadt
+49 6151 16-20017
FAX +49 6151 16-23750
presse@tu-...

Publikation

Unexpectedly large charge radii of neutron-rich calcium isotopes
R. F. Garcia Ruiz, M. L. Bissell, K. Blaum, A. Ekström, N. Frömmgen, G. Hagen, M. Hammen, K. Hebeler, J. D. Holt, G. R. Jansen, M. Kowalska, K. Kreim, W. Nazarewicz, R. Neugart, G. Neyens, W. Nörtershäuser, T.

Recent Laser Spectroscopic Work on Ground State Properties

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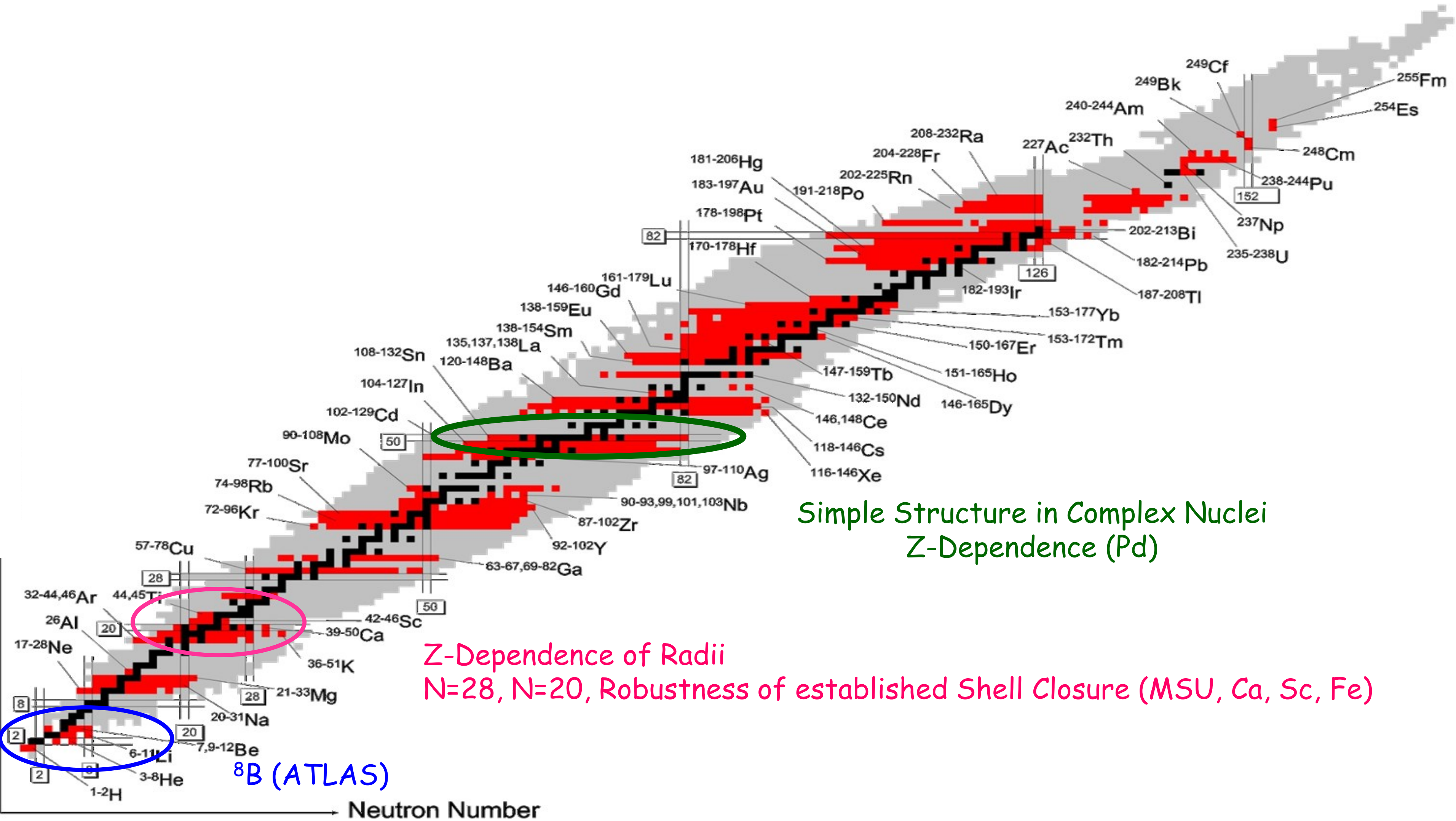


K. Blaum, J. Dilling and W. Nörtershäuser, Phys. Scr. T152, 014017 (2013)

The ^{8}B Proton Halo

VOLUME 69, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 199?

Proton Halo of ^{8}B Disclosed by Its Giant Quadrupole Moment

T. Minamisono,[1] T. Ohtsubo,[1] I. Minami,[1] S. Fukuda,[1] A. Kitagawa,[1],[a] M. Fukuda,[1] K. Matsuta,[1] Y. Nojiri,[1] S. Takeda,[2] H. Sagawa,[3] and H. Kitagawa[4]

[1]*Department of Physics, and Laboratory of Nuclear Studies, Faculty of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560, Japan*

[2]*Department of Chemistry, Faculty of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560, Japan*

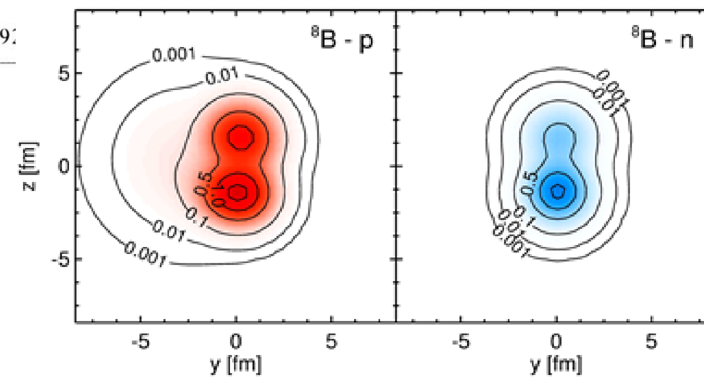
[3]*Department of Physics, Faculty of Science, The University of Tokyo, 7-3-1 Hongou 7-3-1, Bunkyo, Tokyo 113, Japan*

[4]*Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567, Japan*

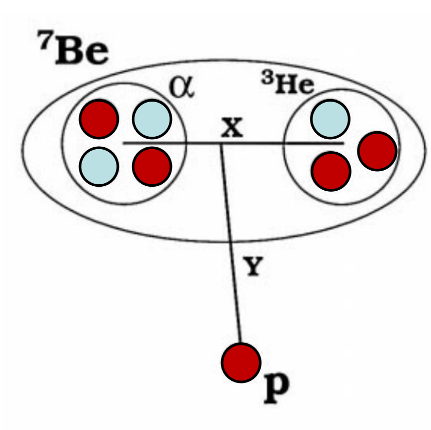
(Received 29 May 1992)

The quadrupole moment of the ^{8}B ($I^{\pi}=2^{+}$, $T_{1/2}=769$ msec) nucleus was measured as $|Q(^{8}\mathrm{B})| = 68.3 \pm 2.1$ mb by use of modified β-NMR. This value is twice as large as the prediction of the Cohen-Kurath shell model. It is found by subtracting the contribution of deeply bound neutrons that the protons in ^{8}B carry more than 90% of the observed moment. The anomalous value is accounted for fairly well by the proton halo due to the loosely bound valence configuration. This is the first experimental evidence for the existence of a proton halo covering a neutron core.

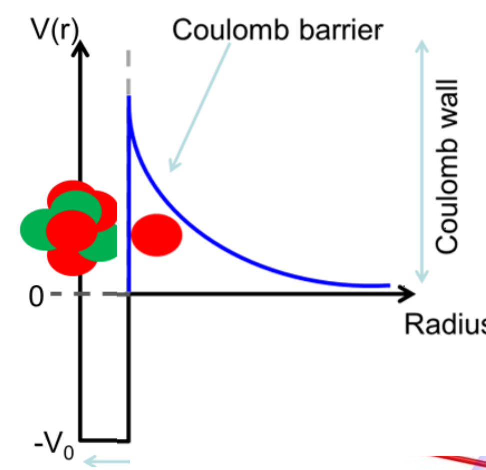
PACS numbers: 21.10.Ky, 21.10.Ft, 27.20.+n



FMD Model calculation (T. Neff, GSI)



M.H. Smedberg *et al.*, Physics Letters B 452 1999 1–7



Isotope Shift Measurement:
The Challenge of Light Isotopes

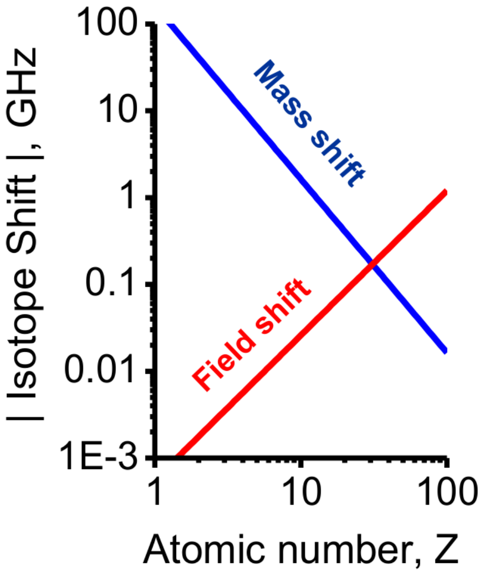
$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

$$\delta\nu_{FS} = F_{el}\,\delta\langle r_c{}^2\rangle$$

Theory: Accuracy of ~100kHz

$$\delta\nu_{MS} \approx 35\ GHz$$
$$\delta\nu_{FS} \approx 10\ \mathrm{MHz/fm^2}$$

$$R_c(^{8}\mathrm{B}) = \sqrt{R_c{}^2\,(^{11}\mathrm{B}) + \delta\langle r_c{}^2\rangle^{11,8}}$$



What we need now:
- suitable transitions in boron
- boron source
- laser spectroscopy

Charge Radii of Light Isotopes

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Measure ! Calculate Calculate Get !

$$\delta\nu_{\mathrm{IS}}^{AA'} = K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + \frac{2\pi Z e}{3} \Delta \left|\Psi(0)\right|^2 \delta \left\langle r^2 \right\rangle^{AA'}$$

^{8,4}He, $2\,^3S_1 \rightarrow 3\,^3P_2$	64 702.5086(9) MHz	1.008 MHz/fm^2
^{11,6}Li, $2s \rightarrow 3s$	36 554.323(9) MHz	1.570 MHz/fm^2
^{11,9}Be$^+$, $2s_{1/2} \rightarrow 2p_{1/2}$	31 560.294(24) MHz	17.02 MHz/fm^2

Yan & Drake, PRA 61, 022504 (2000)
Puchalski & Pachucki PRA 78,058512 (2008)
W. Nörtershäuser et al. PRA 83, 012516 (2011)

(1) Precise Solution of Nonreativistic Schrödinger Equation with Fully Correlated Wavefunctions
(2) Relativistic Corrections
(3) QED Corrections
(4) Nuclear Polarizability

$N_e \leq 3$!!

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
^{10}B: 2.45(12), 2.58(5)

A01: Improve absolute charge radii by elastic electron scattering at S-DALINAC.

New Perspectives: Four-Electron Systems

TECHNISCHE UNIVERSITÄT DARMSTADT

PHYSICAL REVIEW A 89, 012506 (2014)

Isotope shift in a beryllium atom

Mariusz Puchalski,[1,*] Krzysztof Pachucki,[2] and Jacek Komasa[1]

TABLE III. Contributions to the ^{11}Be–^{9}Be isotope shift of the $3\,^1S - 2\,^1S$, $2\,^1P - 2\,^1S$ transition and ionization potential IP($2\,^1S$) in MHz, with exclusion of the finite-size correction. The second uncertainty of $\Delta\nu_{\rm ms}^{\rm the}$ is due to the atomic mass. The nucleus polarizability $\tilde{\alpha}_{\rm pol}(^{11}\mathrm{Be}) = 6.90(69) \times 10^{-7}$ m^{-3} [11], $\tilde{\alpha}_{\rm pol}(^{9}\mathrm{Be}) = 2.90(29) \times 10^{-7}$ m^{-3} [35].

Contribution	$3\,^1S - 2\,^1S$	$2\,^1P - 2\,^1S$	IP($2\,^1S$)
$\Delta\nu^{(2,1)}$	18 907.131(15)	16 020.271(15)	25 558.619(2)
$\Delta\nu^{(2,2)}$	−3.198 2(5)	2.178 8(1)	−5.474 2
$\Delta\nu^{(4,1)}$	2.46(3)	−8.013(12)	3.604(2)
$\Delta\nu^{(5,1)}$	−0.135(4)	0.819(6)	−0.209(2)
$\Delta\nu^{(6,1)}$	−0.041(20)	−0.034(17)	−0.048(24)
$\Delta\nu_{\rm pol}$	0.034(3)	0.066(7)	0.037(4)
$\Delta\nu_{\rm ms}^{\rm the}$	18 906.25(4)(1)	16 015.29(3)(1)	25 556.53(3)(1)
C(MHz/fm^2)	−4.772(8)	−9.334(16)	−5.225(9)

→ charge radius of ^{14}Be,

→ ^{10,12,14}Be charge radii from 2nd transition

Laser SpHERe

Now even 5-Electron Systems in Reach

PHYSICAL REVIEW A **92**, 062501 (2015)

Explicitly correlated wave function for a boron atom

Mariusz Puchalski,[1] Jacek Komasa,[1] and Krzysztof Pachucki[2]

[1] *Faculty of Chemistry, Adam Mickiewicz University, Umultowska 89b, 61-614 Poznań, Poland*

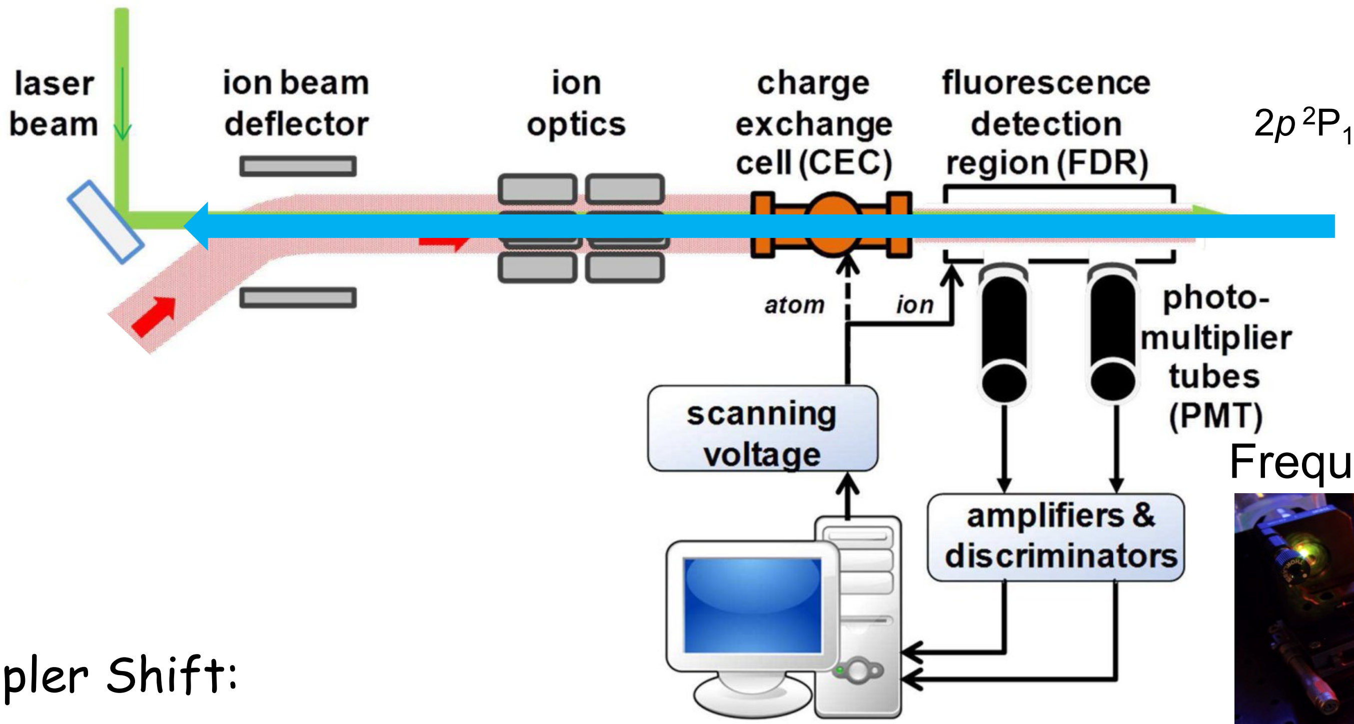
[2] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

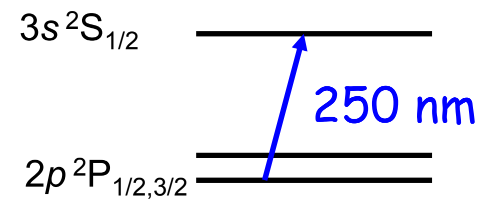
(Received 22 October 2015; published 4 December 2015)

We present results of high-precision calculations for a boron atom's properties using wave functions expanded in the explicitly correlated Gaussian basis. We demonstrate that the well-optimized 8192 basis functions enable a determination of energy levels, ionization potential, and fine and hyperfine splittings in atomic transitions with nearly parts per million precision. The results open a window to a spectroscopic determination of nuclear properties of boron including the charge radius of the proton halo in the ^{8}B nucleus.

DOI: 10.1103/PhysRevA.92.062501 PACS number(s): 31.15.ac, 31.30.J–

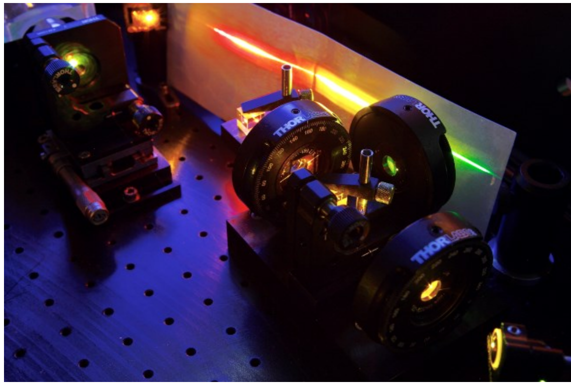
Simplified Setup for ^{8}B Spectroscopy





2nd laser beam

Frequency-Comb required



Doppler Shift:

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

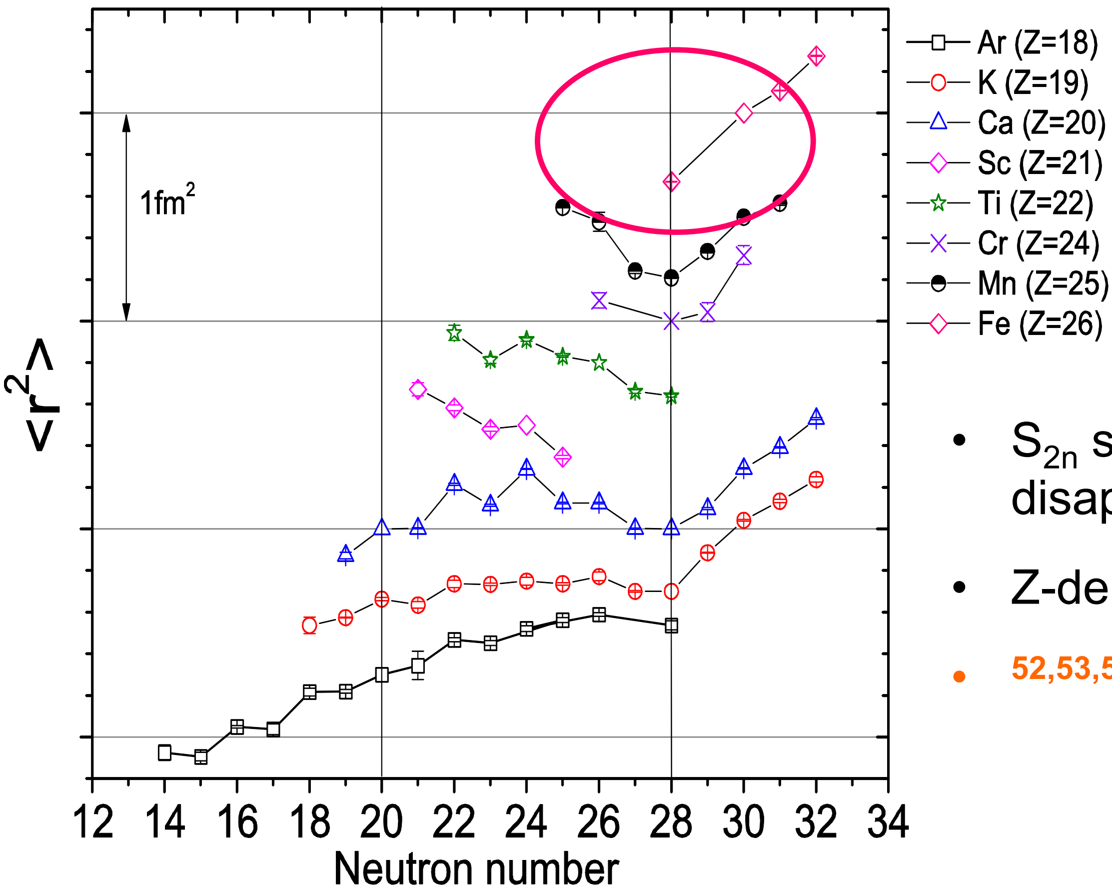
$$\nu_a \cdot \nu_c = \nu_0^2$$

A03: Research plan

N=28: Moments and Charge radii of Fe

Charge radii and magnetic moments from collinear laser spectroscopy

A01

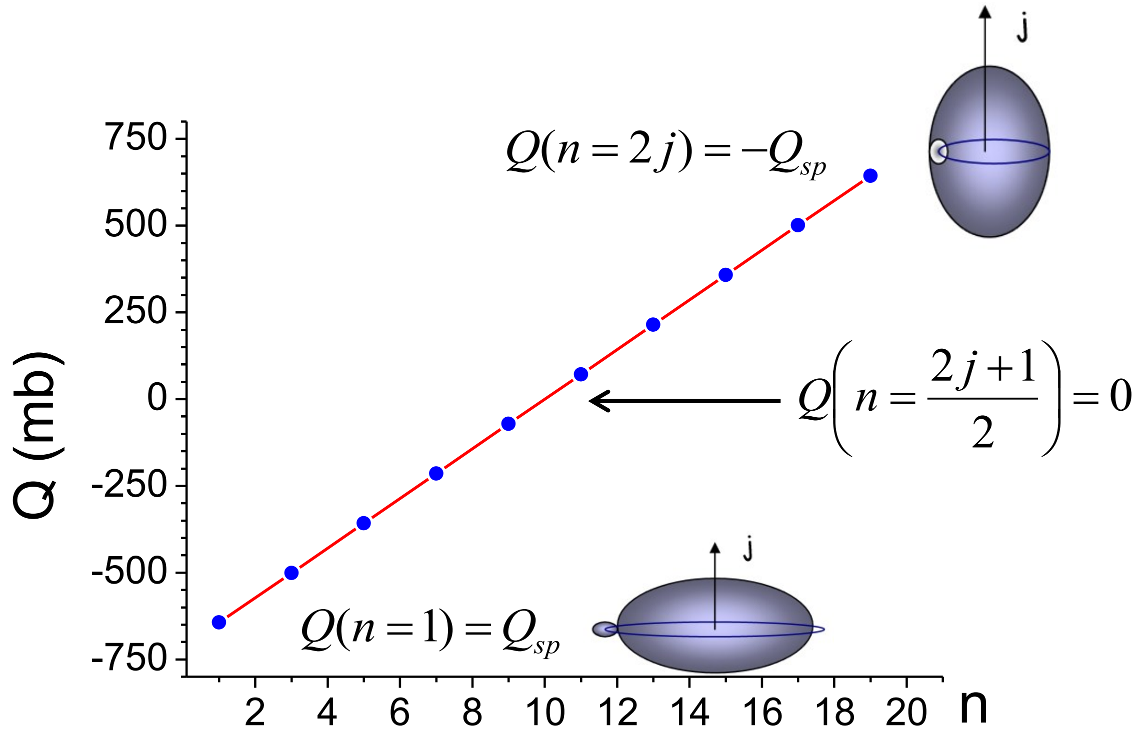


- S_{2n} signature of shell closure at N = 28 disappears at Z = 24
- Z-dependence of the N = 28 shell closure
- ^{52,53,55}**Fe** at BECOLA/NSCL

Quadrupole Moments of Pd 11/2 Isomers - Motivation

$$Q_{sp} = -e^{\text{eff}} \frac{2j-1}{2j+2} \langle r_j^2 \rangle$$

$$Q(n) = Q_{sp} \left(\frac{2j+1-2n}{2j-1} \right)$$

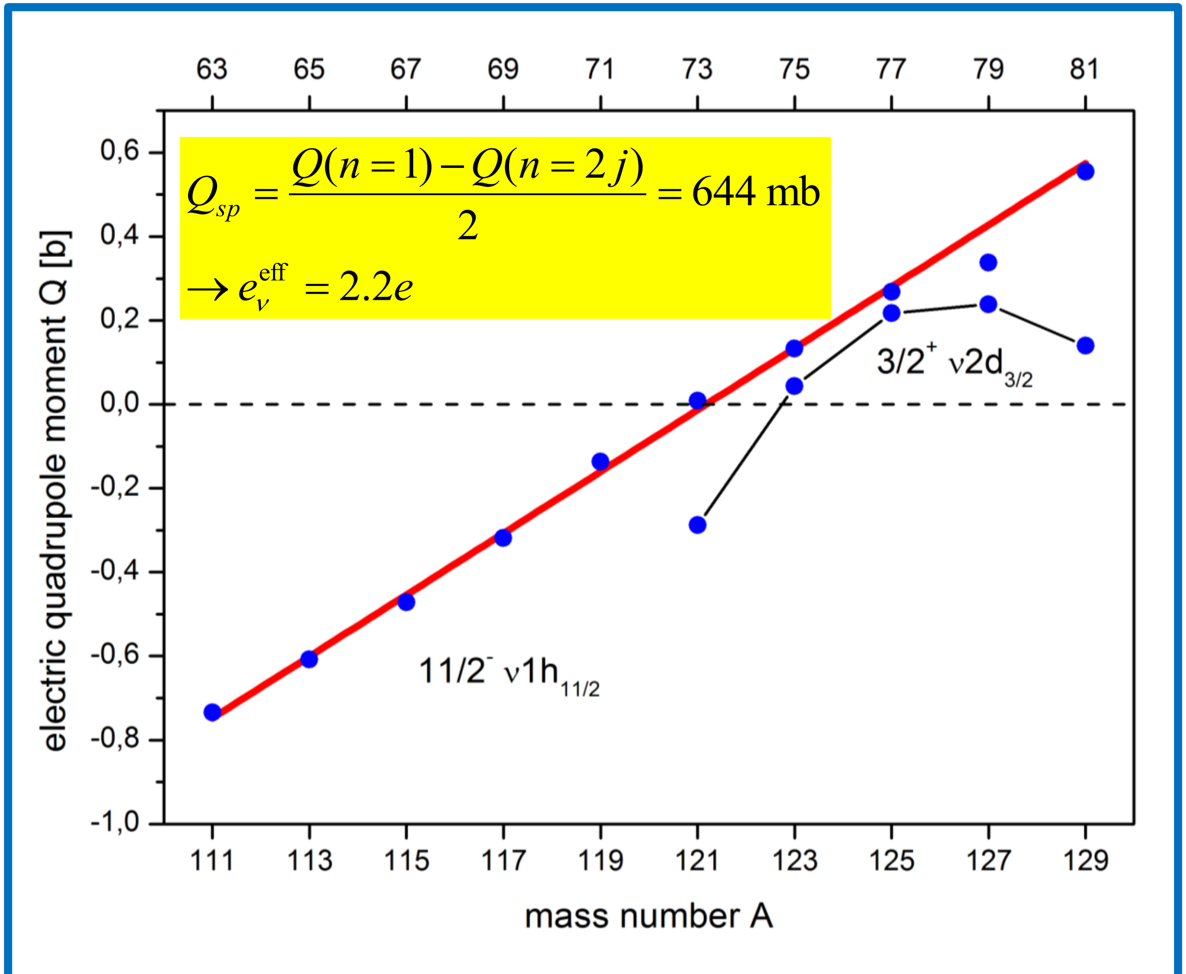


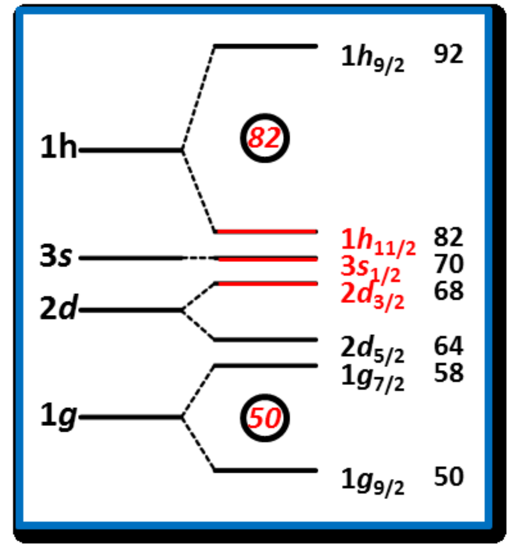
- slope determined by Q_{sp}
- single neutron → oblate deformation (Q<0)
- single neutron hole → prolate deformation (Q>0)

Extraction of Q_{sp}:

$$Q_{sp} = \frac{Q(n=1) - Q(n=2j)}{2}$$

Quadrupole Moments of Pd 11/2 Isomers - Motivation





Capacity of $1h_{11/2}$ niveau:
12 neutrons
→ 6 quad. moments
<u>But:</u> 10 quad. moments

Neutron pairs shared between the neighboring levels.

D. T. Yordanov et al., Phys. Rev. Lett. **110**, 192501 (2013)

→ Check for Z=46 (Palladium, Pd)

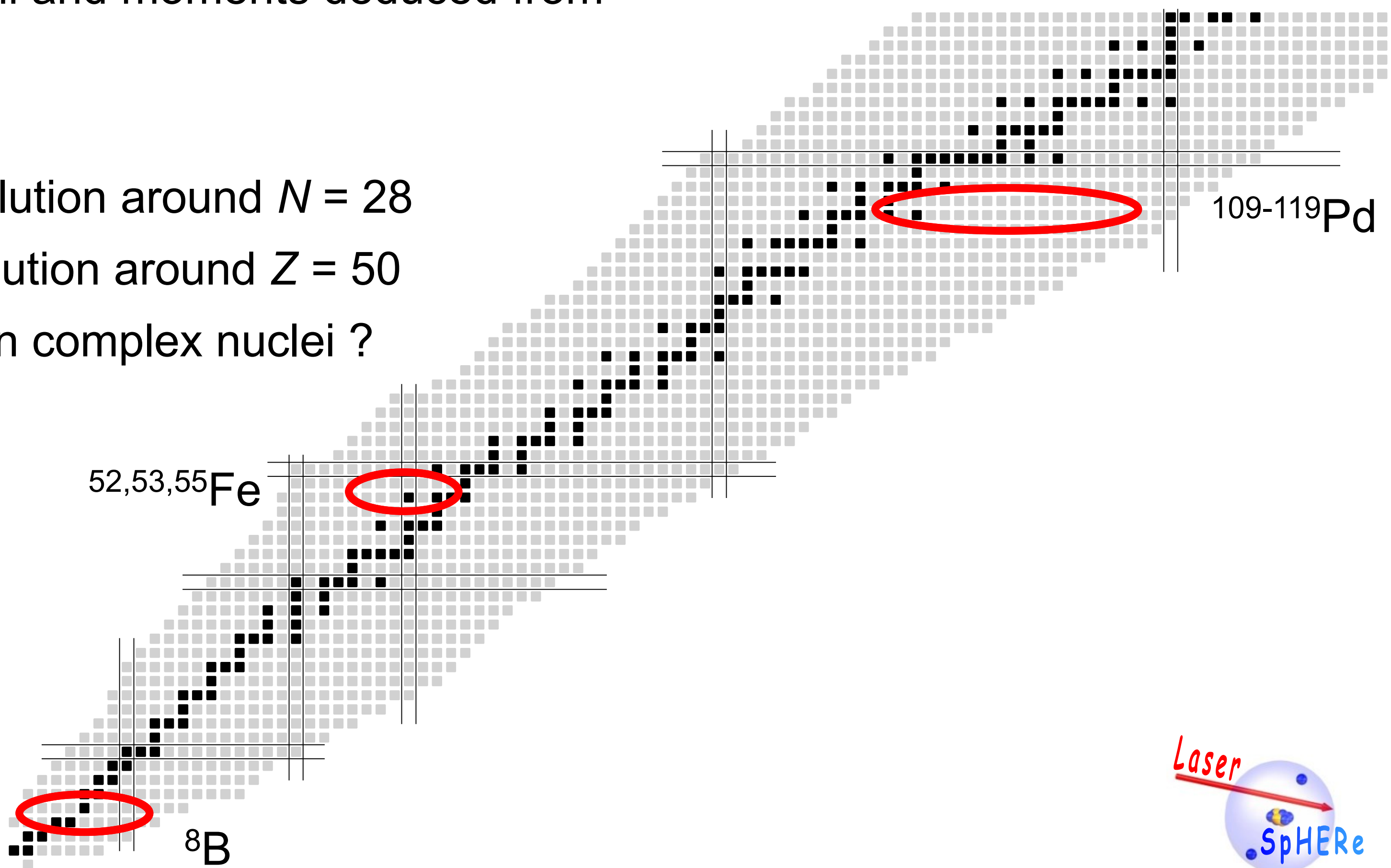
Summary

A01 A03 Key experiments on electromagnetic observables using laser spectroscopy

Nuclear charge radii and moments deduced from laser spectroscopy

- ^{8}B Proton Halo
- ^{52,53,55}Fe shell evolution around *N* = 28
- $^{109\text{-}119}$Pd shell evolution around *Z* = 50

simple structure in complex nuclei ?

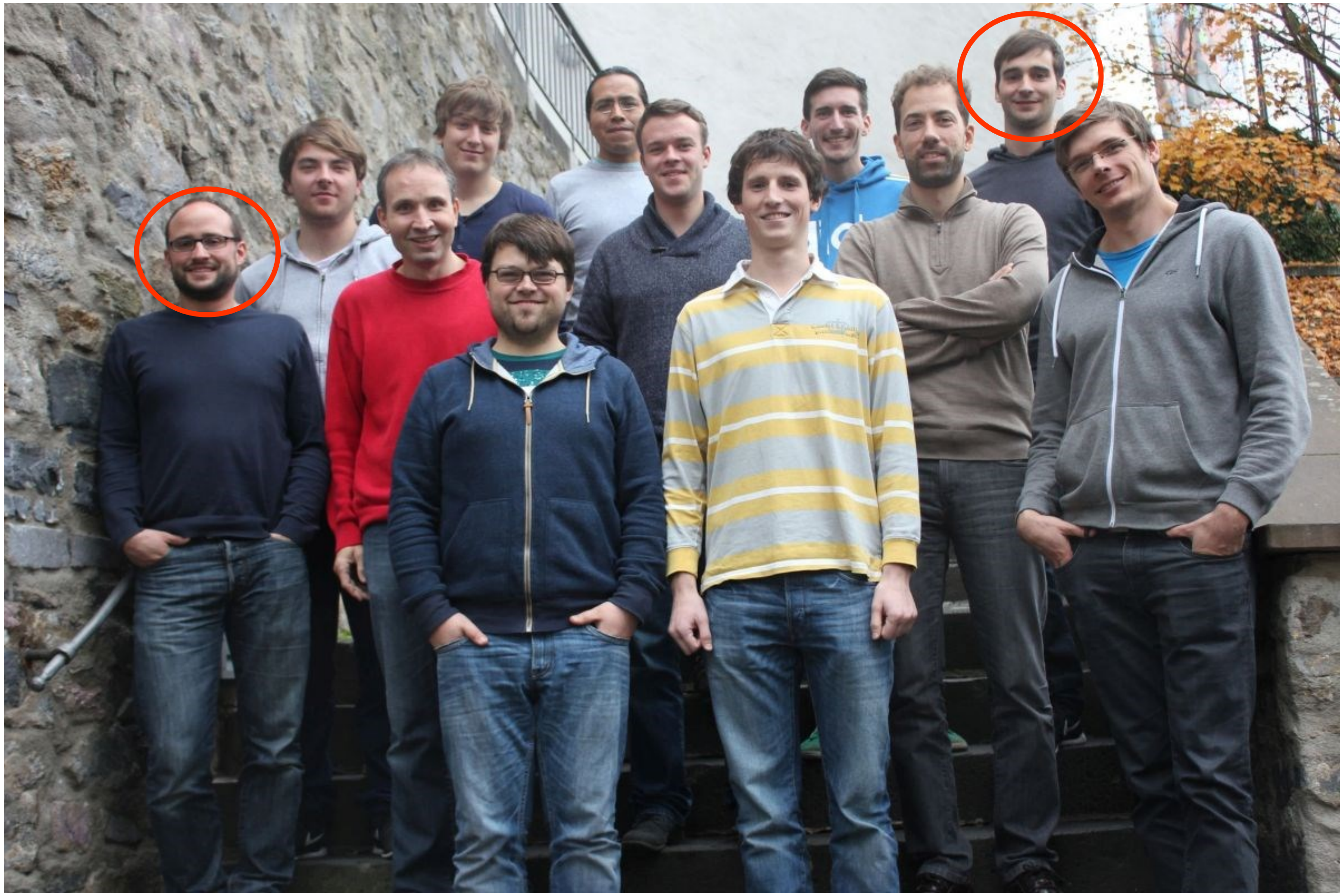


LaserSpHERe

Jörg Krämer

Bernhard Maas

Involvement in A01/A03



Dominic Rossi
(Tom Aumann's group)