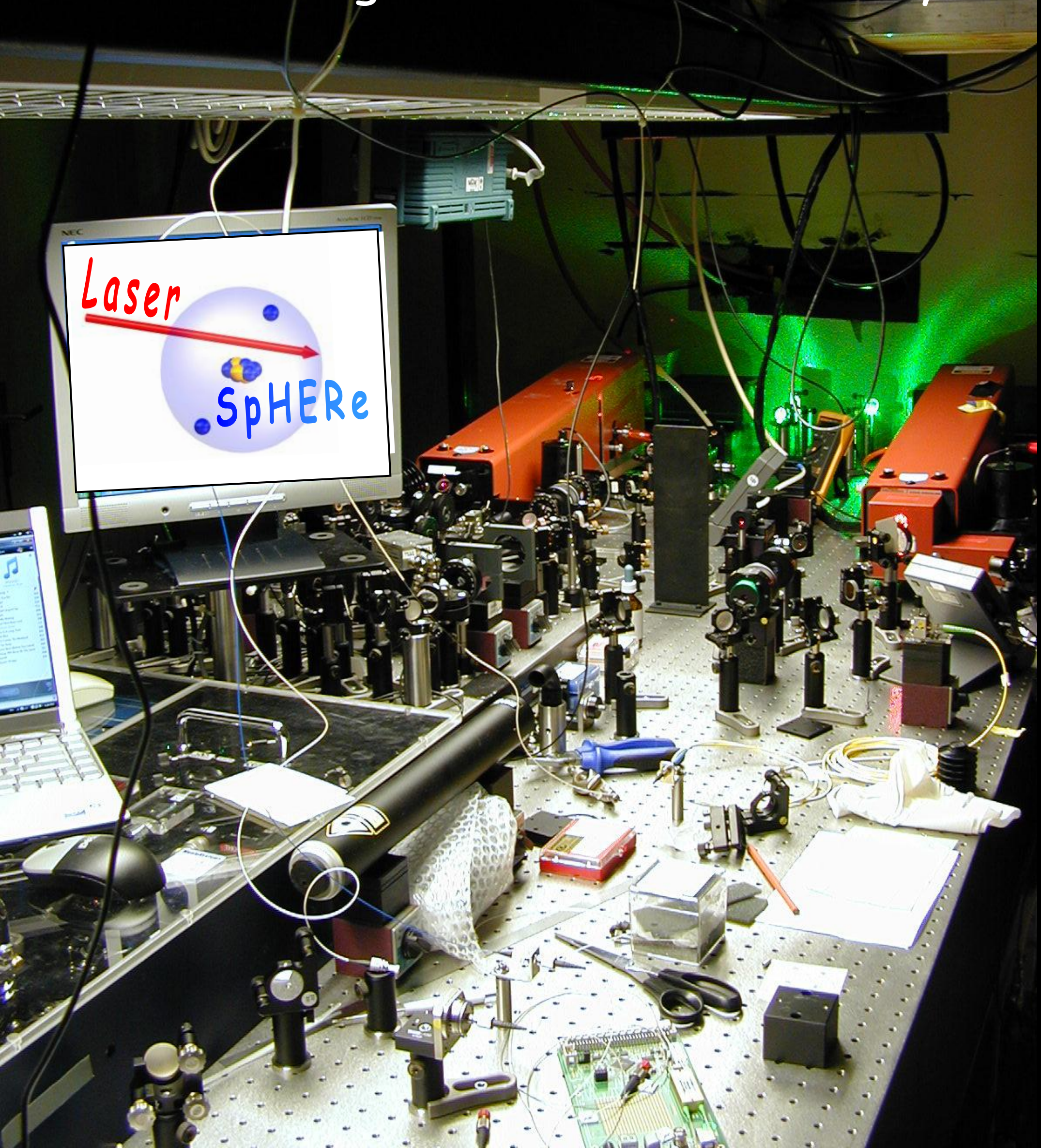
Laser Spectroscopy of Exotic Few-Electron Systems

Investigations at the Boundary of Atomic and Nuclear Physics



W. Nörtershäuser

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

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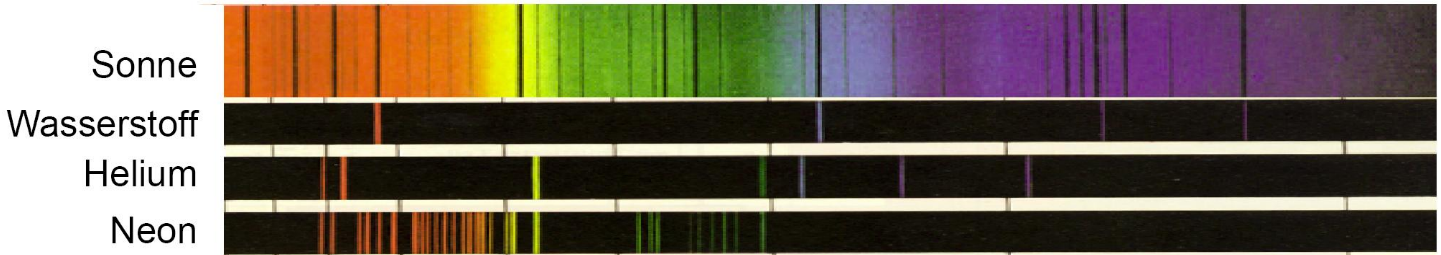
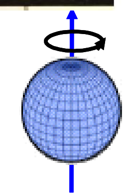
The Atom: A Versatile Laboratory



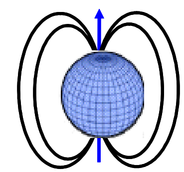
Nuclear Physics

$\langle r^2 \rangle$

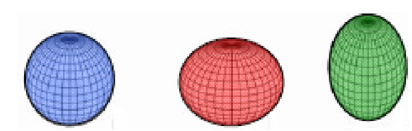
M



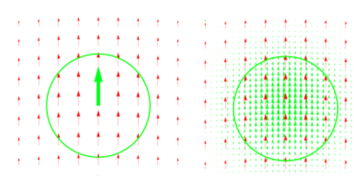
$\mathbf{F} = \mathbf{I} + \mathbf{J}$



$A = \mu_I \frac{\langle B(0) \rangle}{\mathbf{I} \cdot \mathbf{J}}$

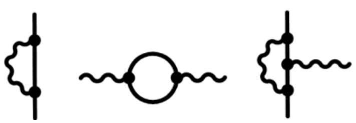


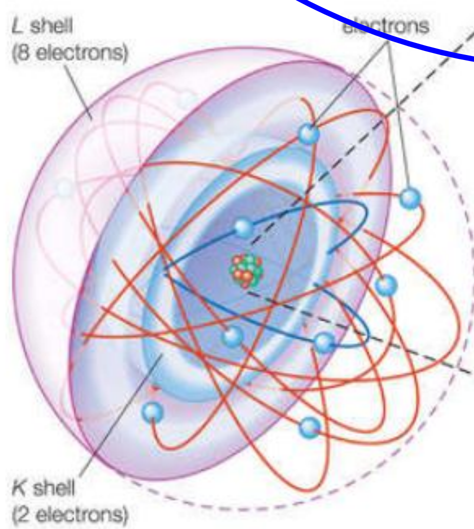
$B = e\, Q_S\, \langle \varphi_{zz}(0) \rangle$



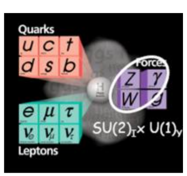
μ(r): Bohr-Weisskopf-Effect

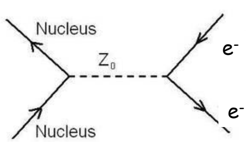
Quantum Electrodynamics



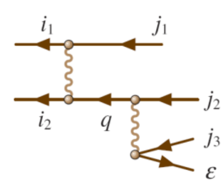


Particle Physics

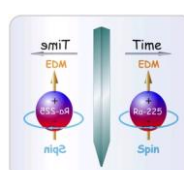




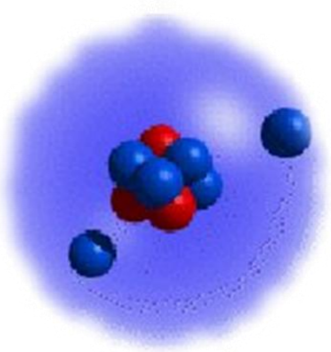
Many-Body Physics



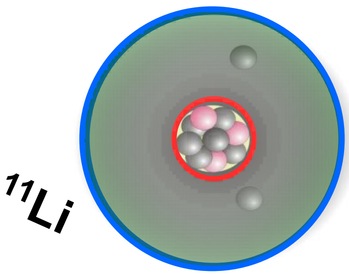
Fundamental Symmetries



Part I: Laser Spectroscopy of Exotic Light Isotopes

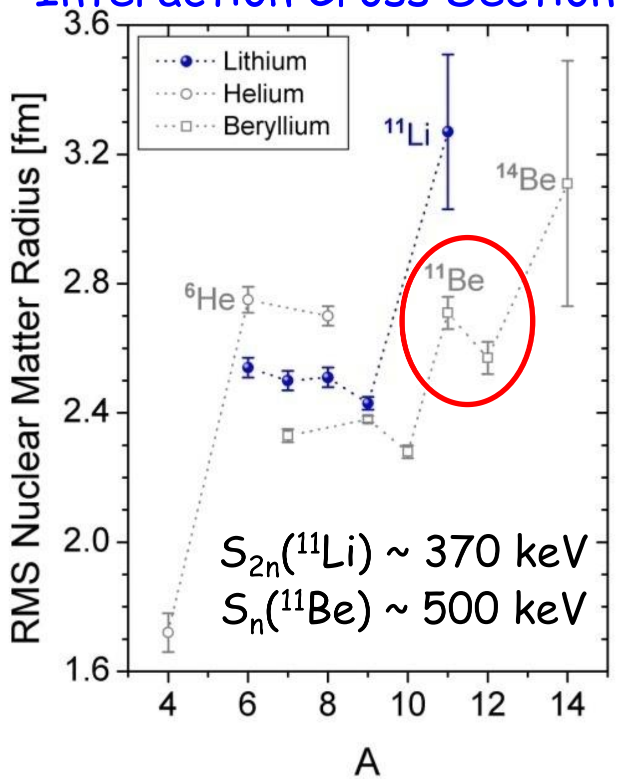


Halo Nuclei



Halo "=" R_{Matter} - R_{Charge} ← Laser spectroscopic determination

Interaction Cross Section

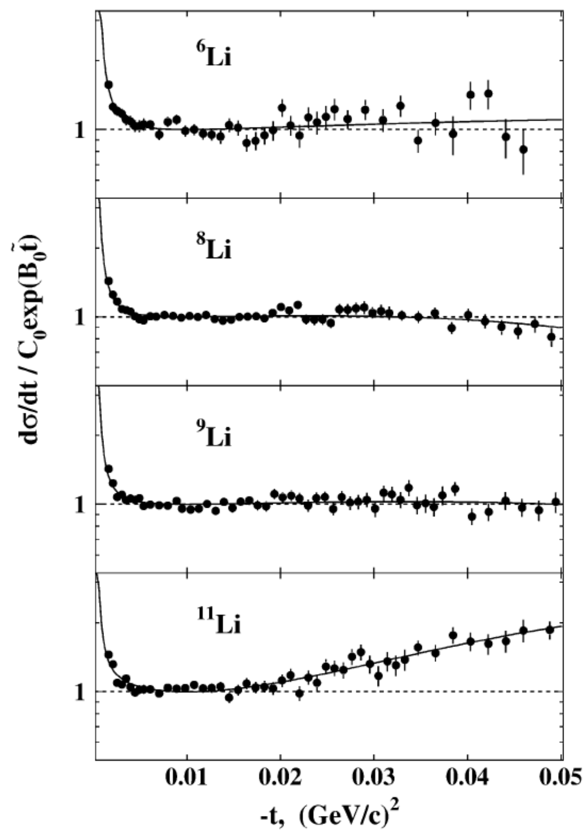


$S_{2n}(^{11}Li)$ ~ 370 keV

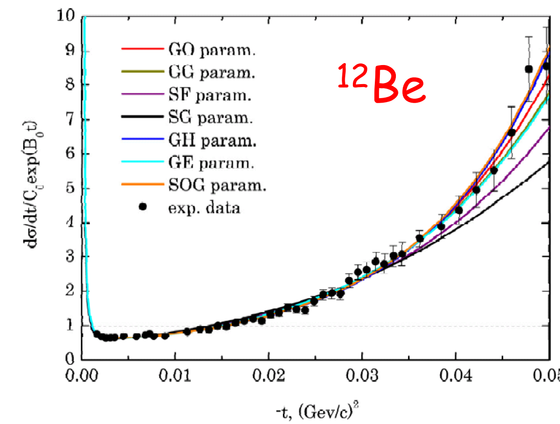
$S_n(^{11}Be)$ ~ 500 keV

Tanihata *et. al.* PRL **55**, 2676 (1985)

Elastic Proton Scattering in Inverse Kinematics



Dobrovolsky et al., Nucl. Phys. A **766**, 1 (2006)

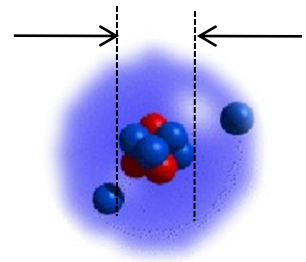


S. Ilieva, PhD Thesis, University Mainz (2009)

Motivation

(a) Exotic Structure of Halo Nuclei

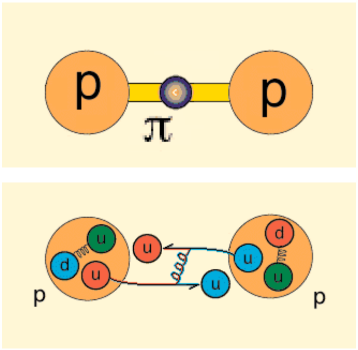
Model-Independent Approach
to the Core Size in Halo Nuclei

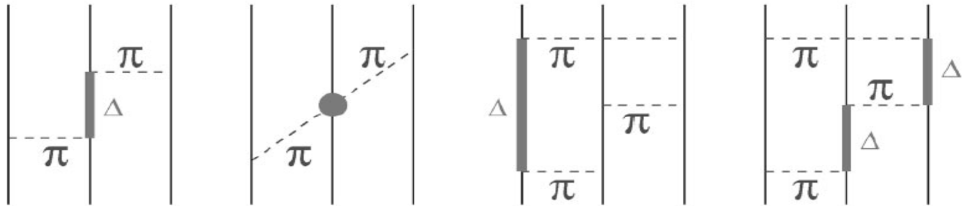


(b) Validating ab-initio Nuclear Structure Calculations

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

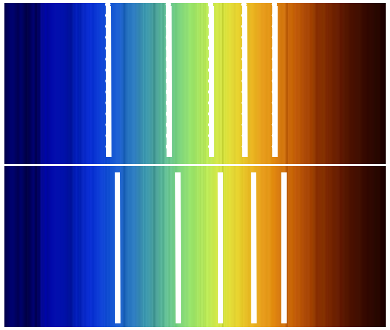
(Greens-Function Monte Carlo, No-Core Shell Modell, Fermionic Molecular Dynamics)





Isotope Shift

Isotop 1



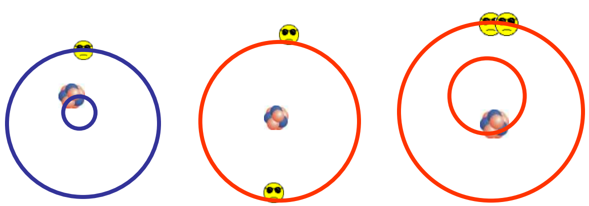
Isotop 2

= Frequency difference in an electronic transition between two isotopes

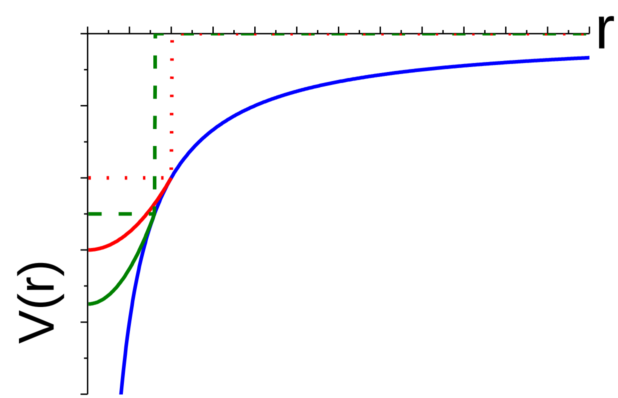
$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS}$$

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

Mass Effect,
nuclear motion



Field Shift
finite size of the nucleus



Charge Radii from Isotope Shifts

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

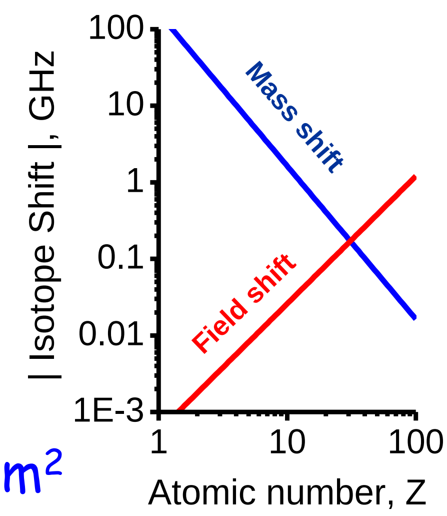
$$\delta\nu_{FS} = \underbrace{\frac{2\pi}{3}\Delta|\psi(0)|^2}\,\delta\langle r^2\rangle$$

EXPERIMENT ($\delta\nu_{IS}$)

THEORY ($\delta\nu_{MS}$, $\frac{2\pi}{3}\Delta|\psi(0)|^2$)

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

$^{6}\mathrm{Li}$-$^{11}\mathrm{Li}$: ≈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

Expansion of Isotope Shift Terms

Energy of an atomic state

$$E_{tot} = E_{NR} + \alpha^2 E_{Rel} + \alpha^3 E_{QED} + \ldots + \Delta E_{\text{nuclearsize}}$$

Expand in terms of μ/M, with $\mu = m_e M/(M+m_e)$

$$E_{NR} = E_{NR}^{(0)} + \frac{\mu}{M} E_{NR}^{(1)} + \left(\frac{\mu}{M}\right)^2 E_{NR}^{(2)} + \ldots$$

Mass polarization, 1st and 2nd order

$$E_{Rel} = E_{Rel}^{(0)} + \frac{\mu}{M} E_{Rel}^{(1)} + \ldots$$

Relativistic mass, spin-orbit, spin-spin, spin-other orbit, relativistic nuclear recoil, …

$$E_{QED} = E_{QED}^{(0)} + \frac{\mu}{M} E_{QED}^{(1)} + \ldots$$

Anomalous magnetic moment, vacuum polarization, self energy, …

Isotope shift

$$\Delta E(a-b) = \left[\left(\frac{\mu}{M}\right)_a - \left(\frac{\mu}{M}\right)_b\right]\left(E_{NR}^{(1)} + \alpha^2 E_{Rel}^{(1)} + \alpha^3 E_{QED}^{(1)}\right) + \left[\left(\frac{\mu}{M}\right)_a^2 - \left(\frac{\mu}{M}\right)_b^2\right] E_{NR}^{(1)} + \ldots + \Delta E_{nuc,a} - \Delta E_{nuc,b}$$

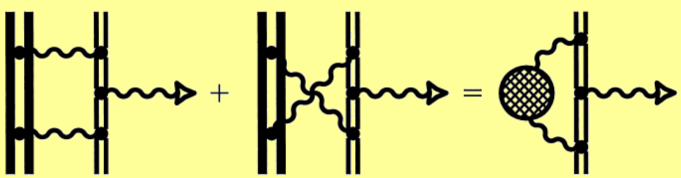
Results of Mass Shift Calculations

Isotope	Yan & Drake	Puchalski & Pachucki
^{7}Be	49225.779 (38)	- 49 225.744 (35)(9)
^{9}Be	0	0
^{10}Be	17 310.442 (12)	17 310.459 (13)(11)
^{11}Be	31560.198(32)	31 560.245 (31)(12)
^{12}Be	43 390.168(39)	43 390.18(3)(18)

Isotope	M(Be) amu	Ref
^{7}Be	7.016 929 83 (21)	AME2003
^{9}Be	9.012 182 20 (40)	TITAN
^{10}Be	10.013 534 74 (13)	TITAN
^{11}Be	11.021 661 55 (62)	TITAN
^{12}Be	12.026 920 7 (23)	TITAN
^{14}Be	14,042 89 (14)	AME2003

ν_{pol} = 208 kHz

Nuclear Polarizability



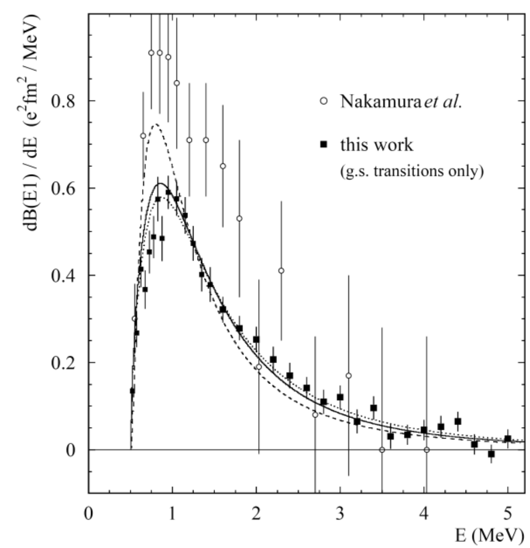
Significant correction to the isotope shift of ^{11}Be

$$\nu_{\rm pol} = -m\alpha^4 \left\langle \sum_a \delta^3(r_a) \right\rangle (m^3 \tilde{\alpha}_{\rm pol})$$

$$\tilde{\alpha}_{\rm pol} = \frac{16\alpha}{3} \int dE \frac{1}{e^2} |\langle \phi_N | \vec{d} | E \rangle|^2 \int_0^\infty \frac{dw}{w} \frac{E}{E^2+w^2} \times \frac{1}{(\kappa+\kappa^\star)} \left[1 + \frac{1}{(\kappa+1)(\kappa^\star+1)} \left(\frac{1}{\kappa+1} + \frac{1}{\kappa^\star+1} \right) \right]$$

$$|\langle \phi_N | \vec{d} | E \rangle|^2 = \frac{4\pi}{3} \frac{dB(E1)}{dE}$$

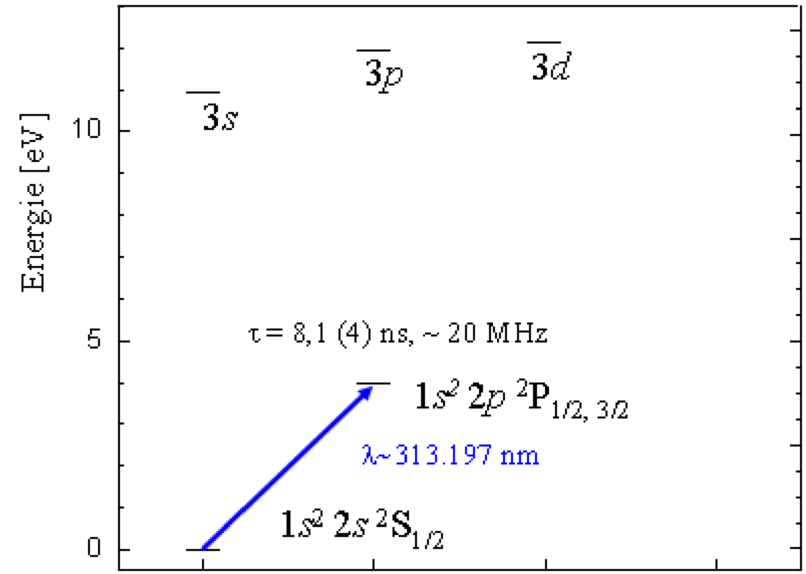
Puchalski & Pachucki, PRA 78, 052511 (2008)

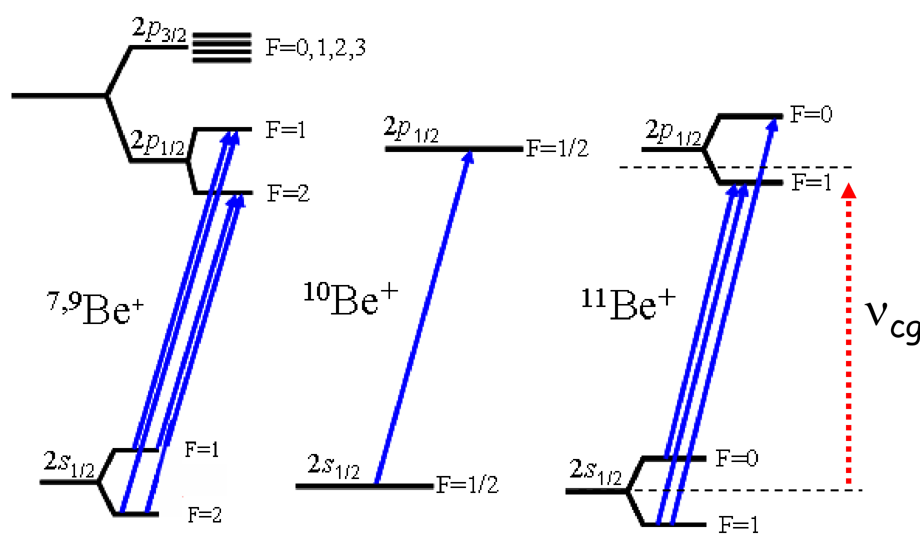


R. Palit et al., PRC 68, 034318 (2003)

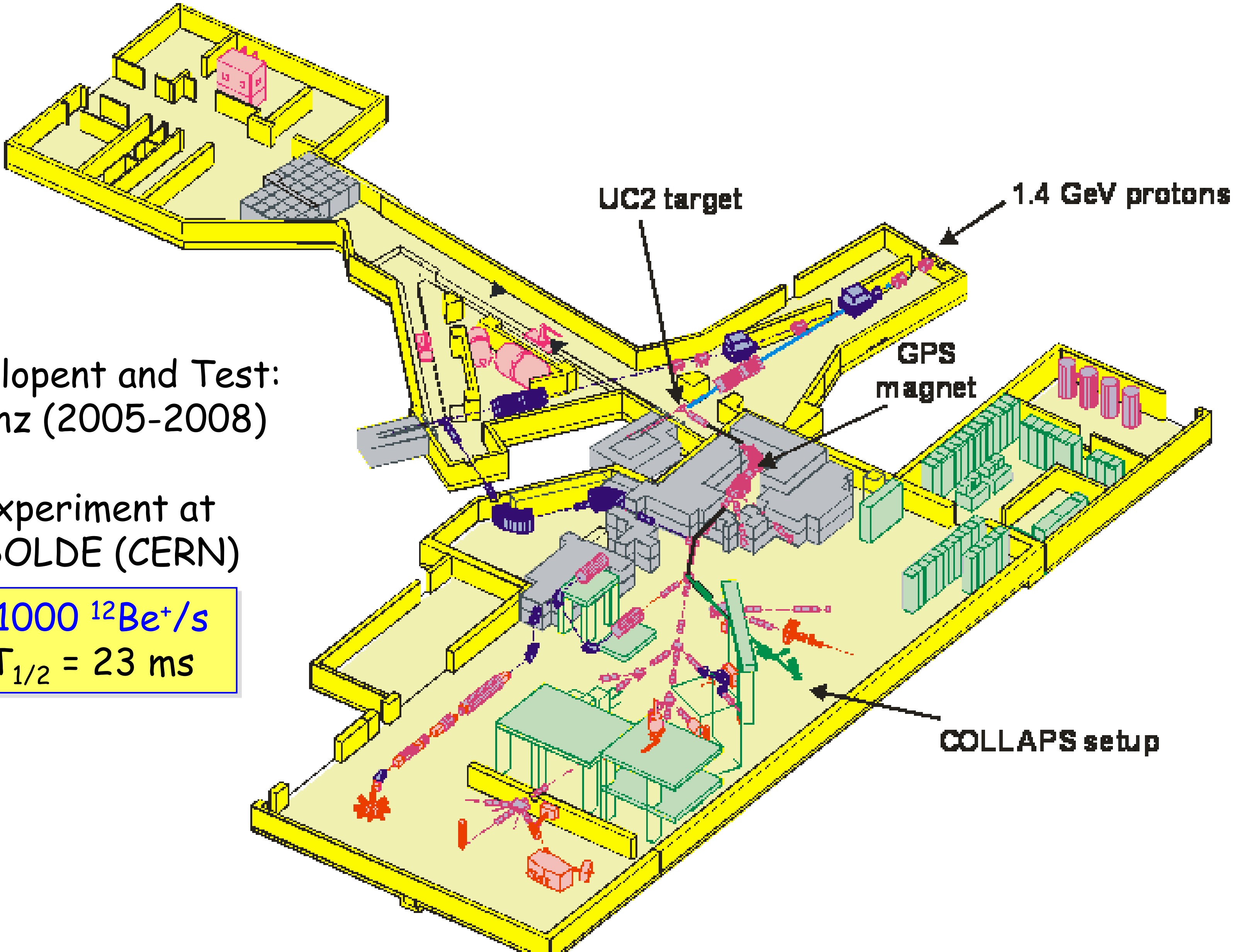
Production Rates and Transition

Properties		Yields at ISOLDE
Be-7	$\tau_{1/2}$=53 d I=3/2	1.4×10^{10} s^{-1}
Be-9	stable I=3/2	
Be-10	1.5 Ma I=0	6.0×10^{9} s^{-1}
Be-11	13.6 s I=1/2	7.0×10^{6} s^{-1}
Be-12	23 ms I=0	1000 s^{-1} !
Be-14	4 ms I=0	4 s^{-1} ! !





The ISOLDE Facility

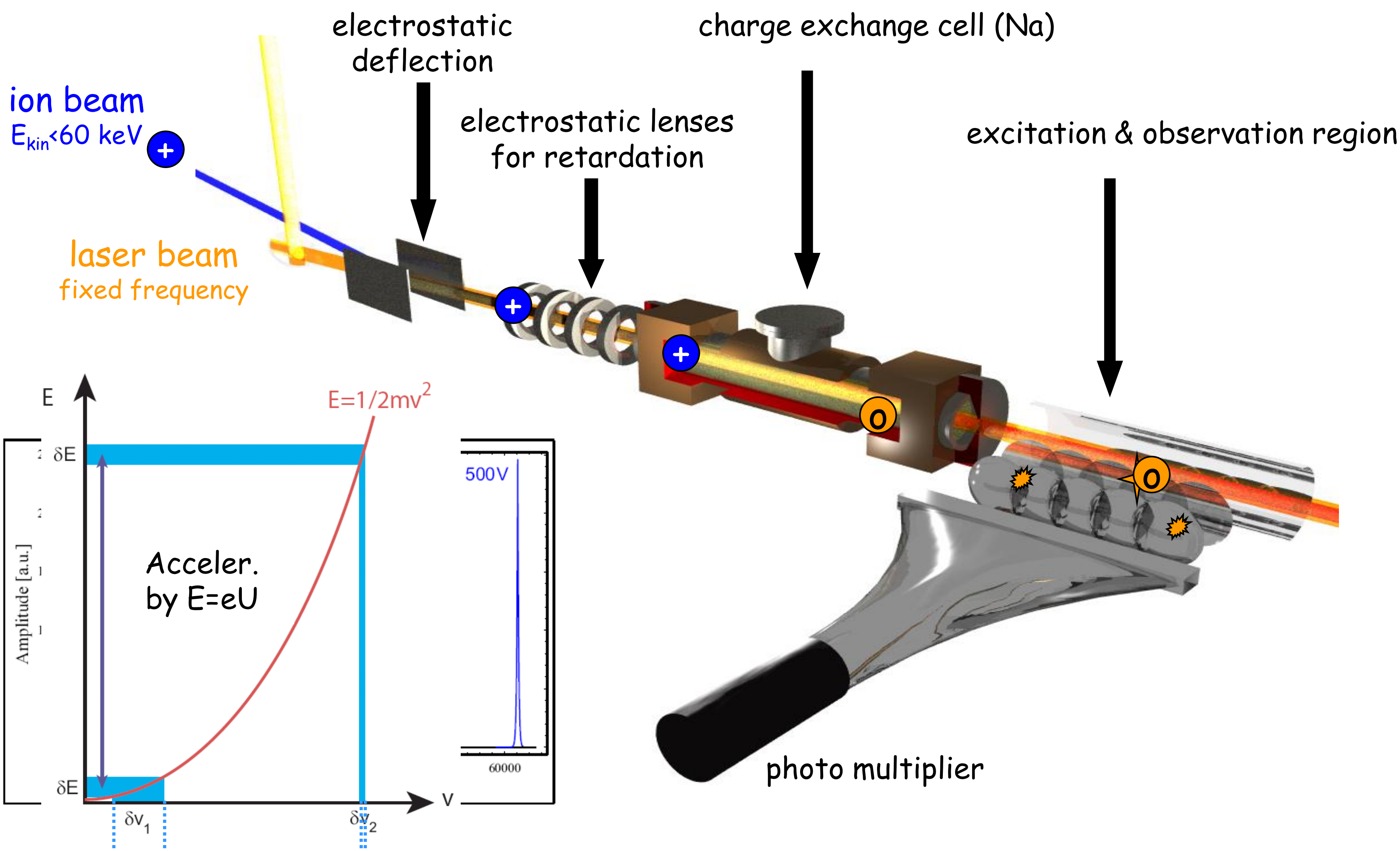


Developent and Test:
Mainz (2005-2008)

Experiment at
ISOLDE (CERN)

~ 1000 $^{12}Be^{+}/s$
$T_{1/2}$ = 23 ms

Collinear Laser Spectroscopy
The Principle

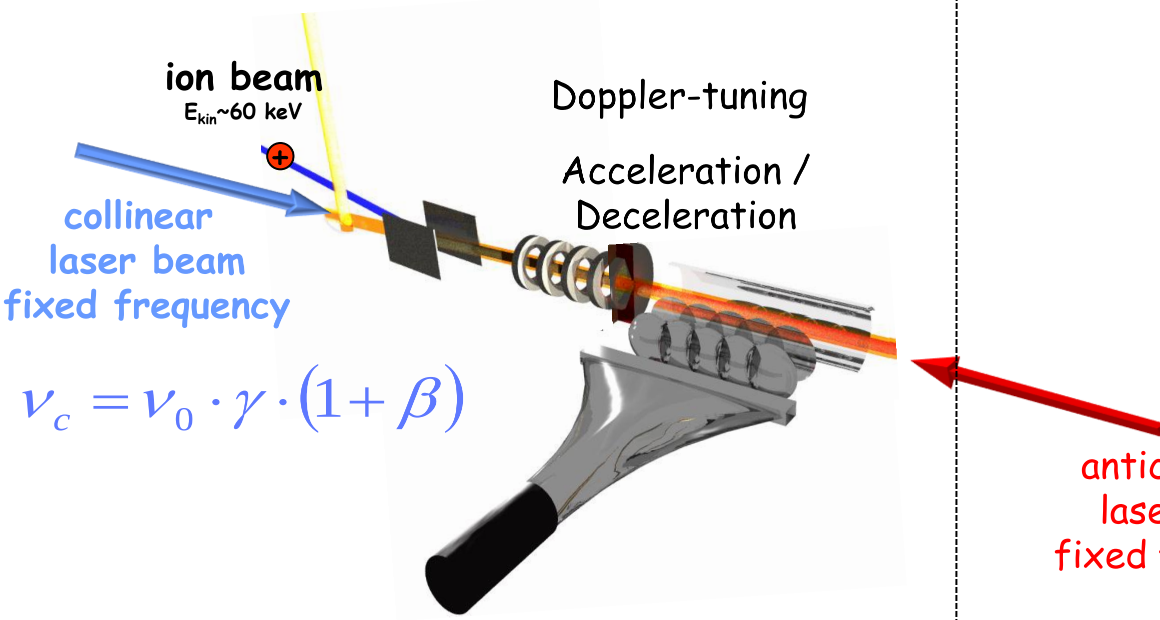


Collinear Laser Spectroscopy
Limitations for Light Elements

The Solution

Laser SpHERe

„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) !!

OUR APPROACH

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

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

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

Completely independent of U !

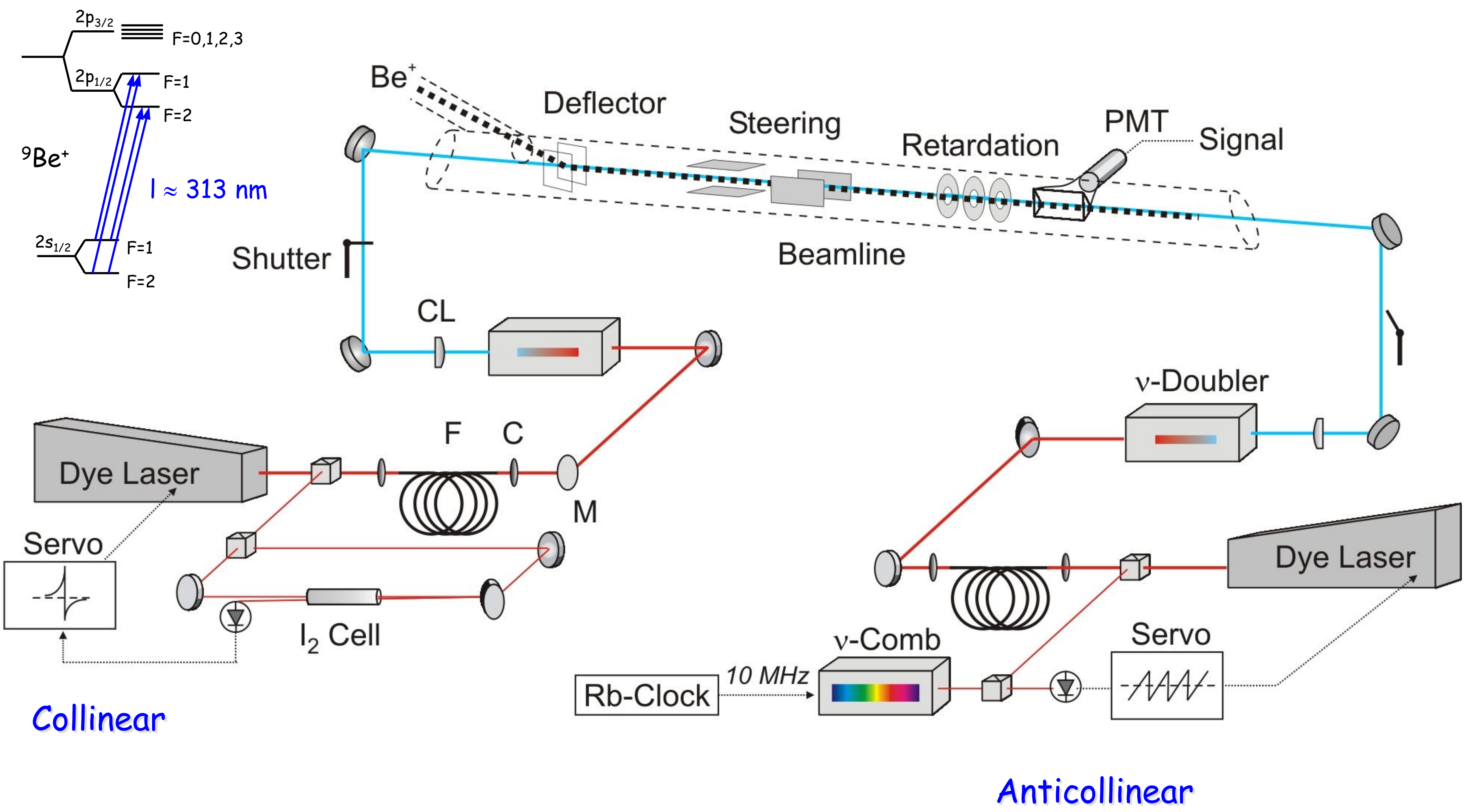
<u>Requirements:</u>

Measure absolute frequencies

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

Dedicated Laser System for absolute Frequency Measurements

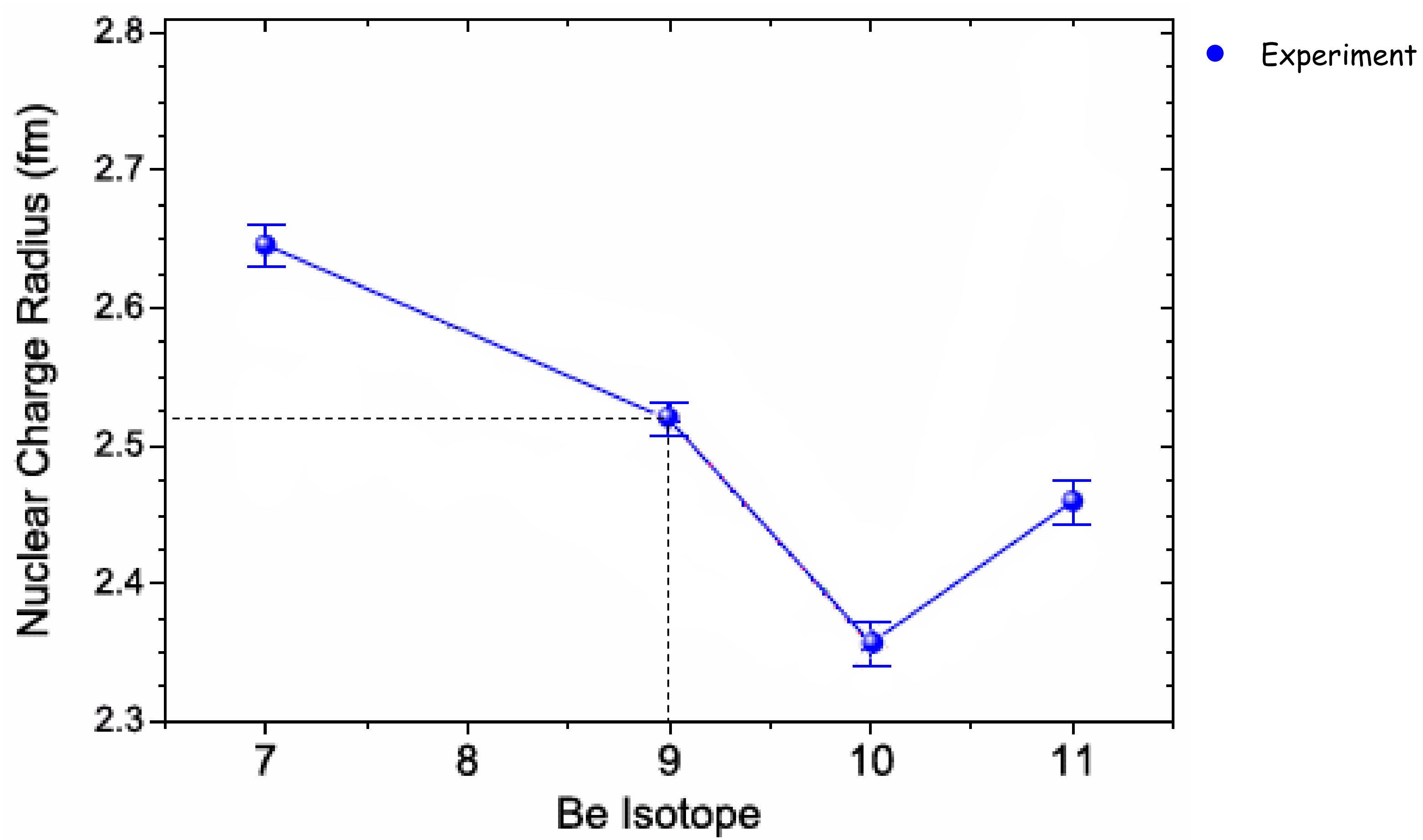
Experimental Setup



Charge Radii of Be Isotopes

Reference Point: ^{9}Be

Electron Scattering: $r_c(^{9}Be) = 2.519(12)$ fm, [J.A. Jansen et al., Nucl.Phys.A 188, 337 (1972)]



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

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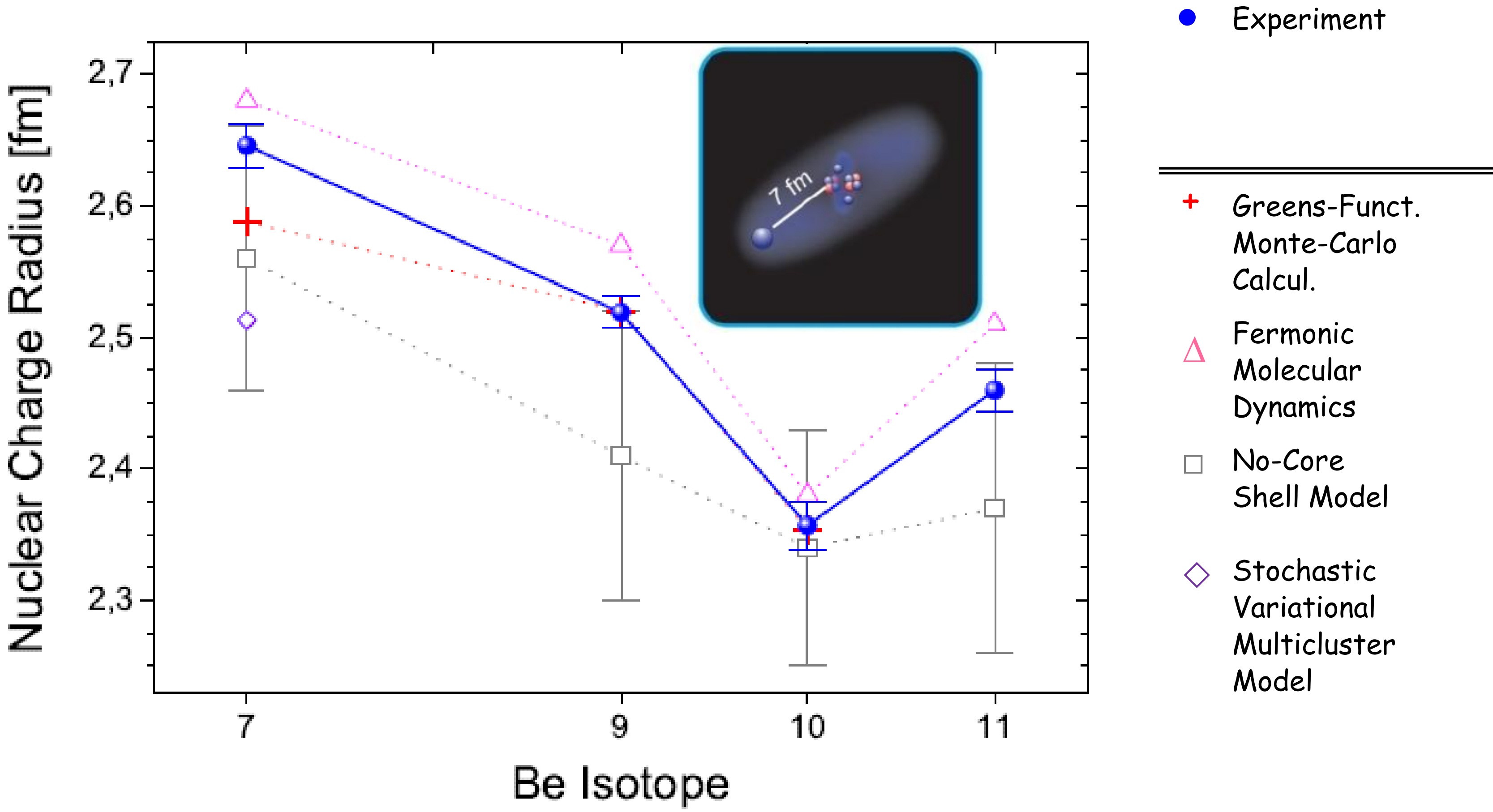
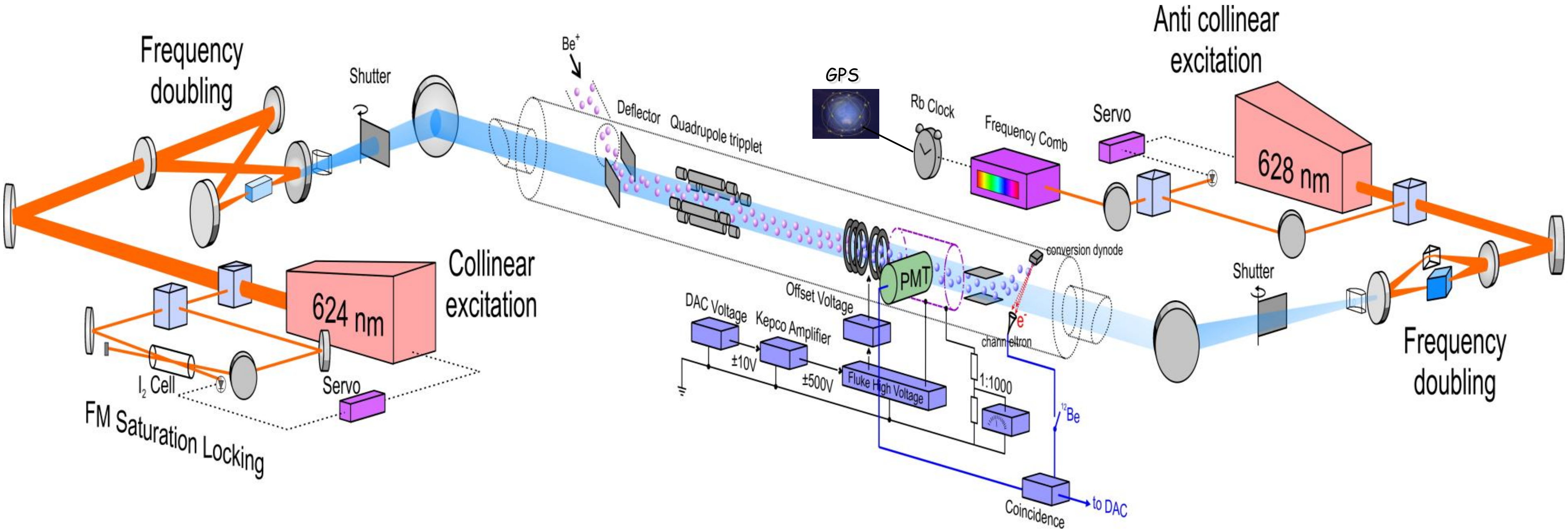


W. Nörtershäuser *et al.*, PRL **102**, 062503 (2009)
M. Zakova et al., Europ. Phys. J. G **37**, 055107 (2010)

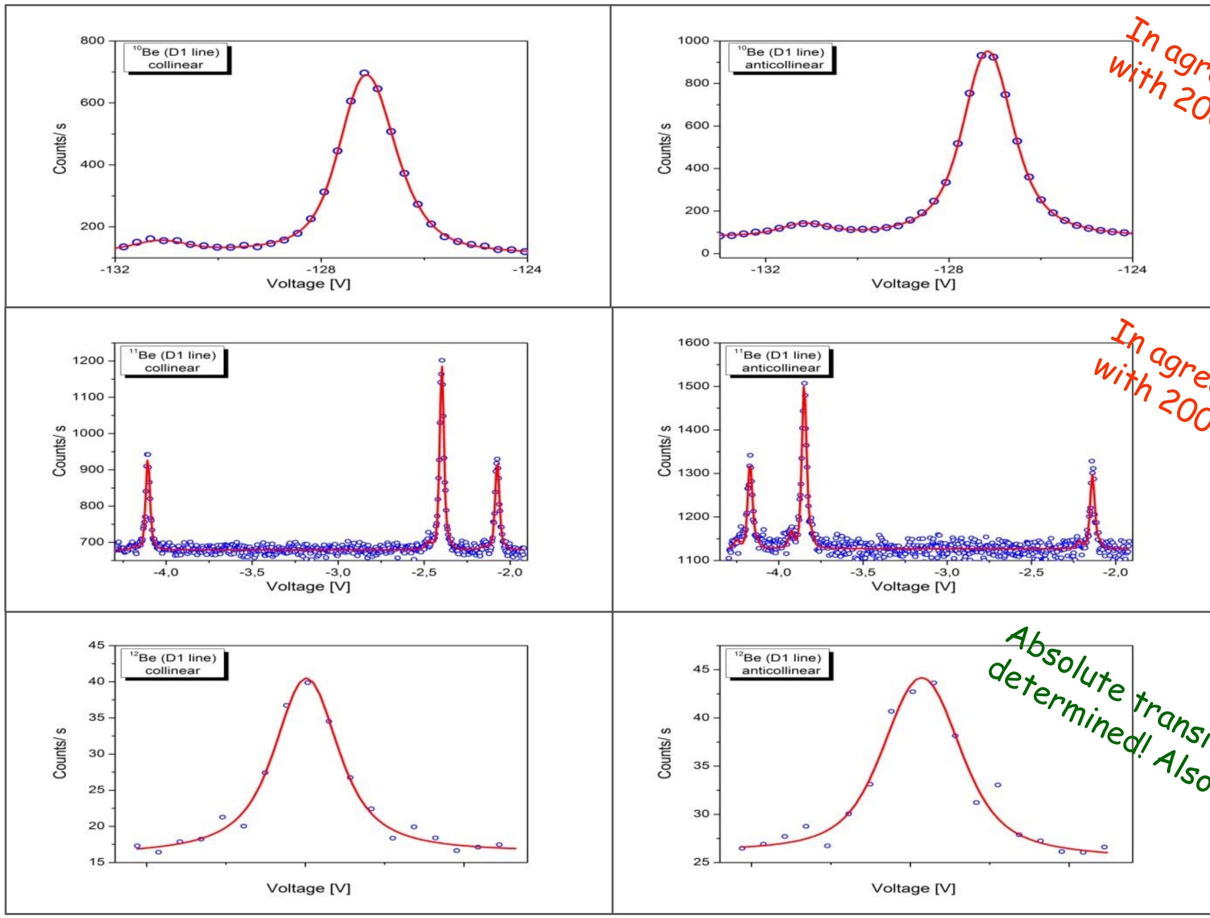
Experimental Setup for ^{12}Be



Results

Remeasured absolute transition frequencies for $^{10,11}Be^{+}$ and $^{12}Be^{+}$

A factors $2s_{1/2}$ and $2p_{1/2}$ states & magnetic moment for ^{11}Be



In agreement with 2008

In agreement with 2008

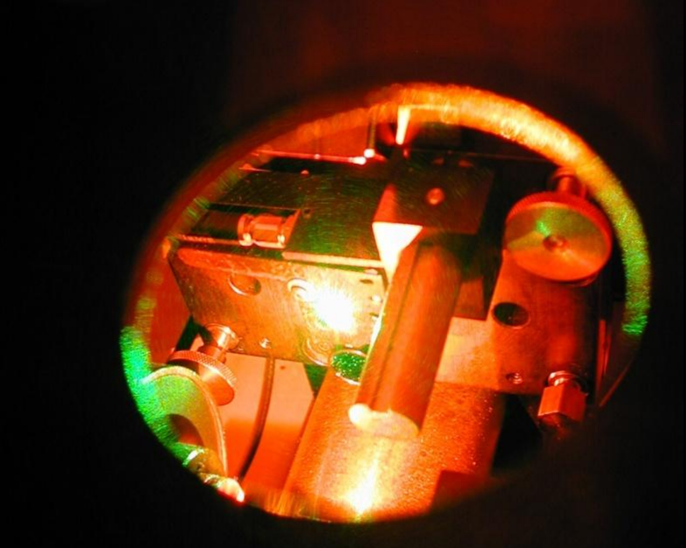
Absolute transition frequency determined! Also D2-Line!

Measuring Time/ Plot:

^{10}Be: 150 sec.
^{11}Be: 2000 sec.
^{12}Be: 7200 sec.

Isotope shift relative to ^{10}Be →

Nuclear charge radii



Krieger A, Geppert Ch, Frömmgen N, Hammen M, Krämer J, Neugart R.

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Nörtershäuser W, Sánchez R

GSI

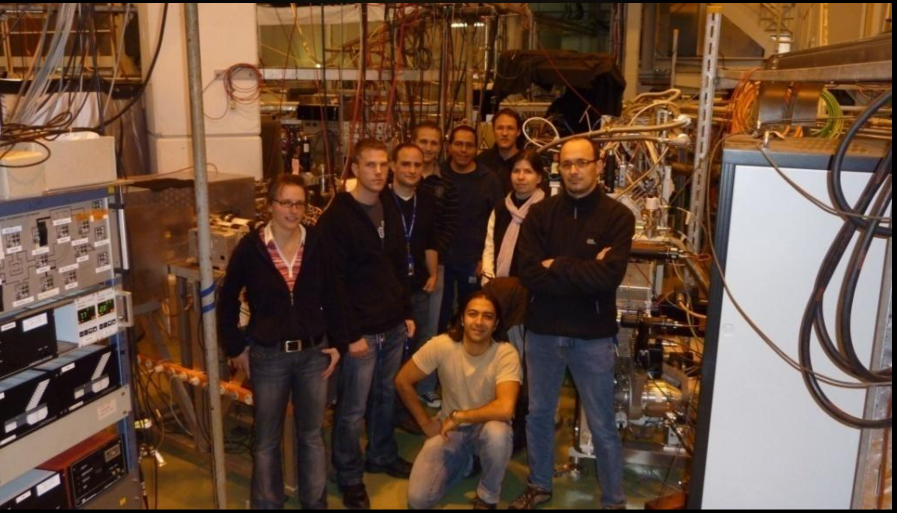
Kowalska M

ISOLDE CERN

Bissell M L

KATHOLIEKE UNIVERSITEIT LEUVEN

Blaum K, Kreim K, Yordanov D



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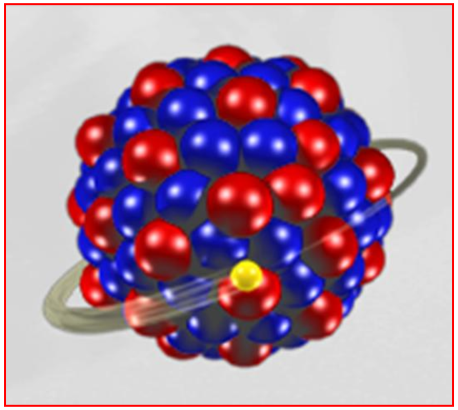
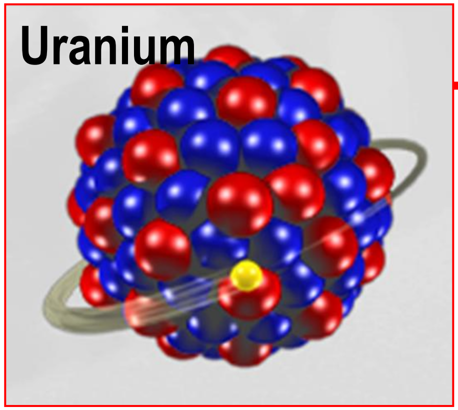
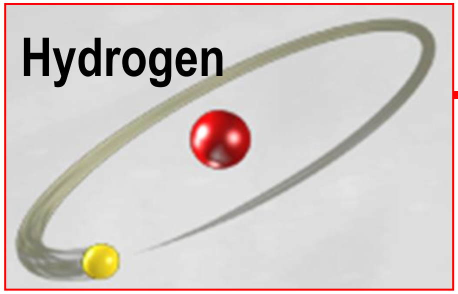
Part II: Laser Spectroscopy of Hydrogen- and Lithiumlike Heavy Ions

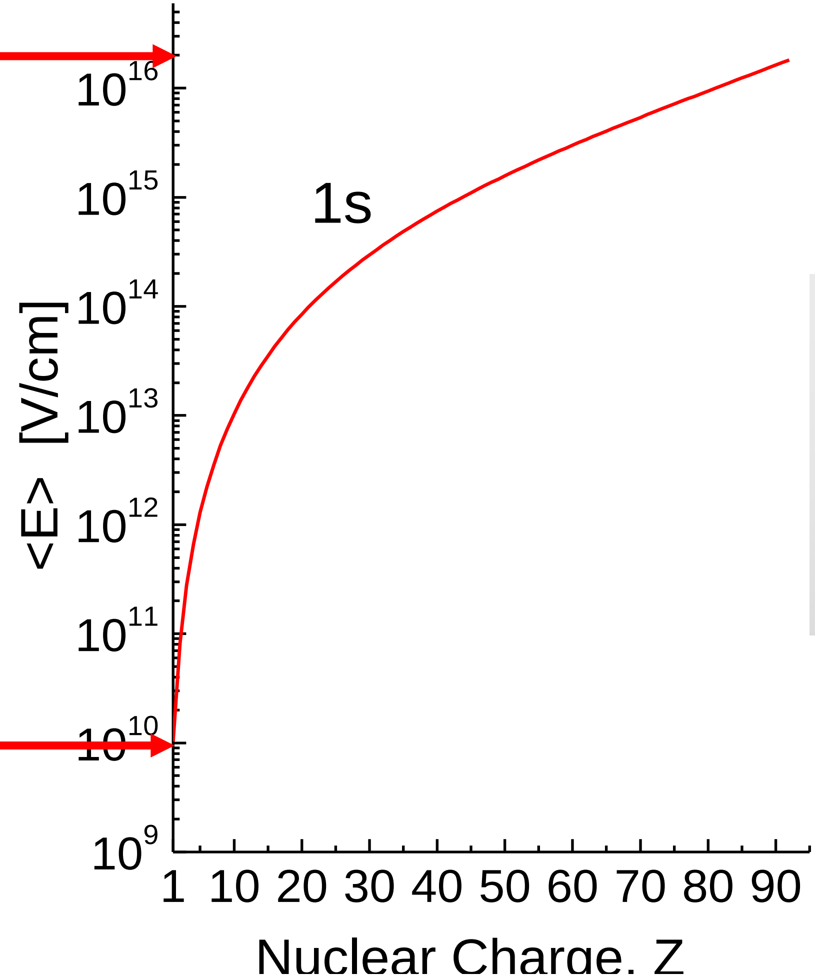


Highly Charged Heavy Ions

Extreme Static Electromagnetic Fields





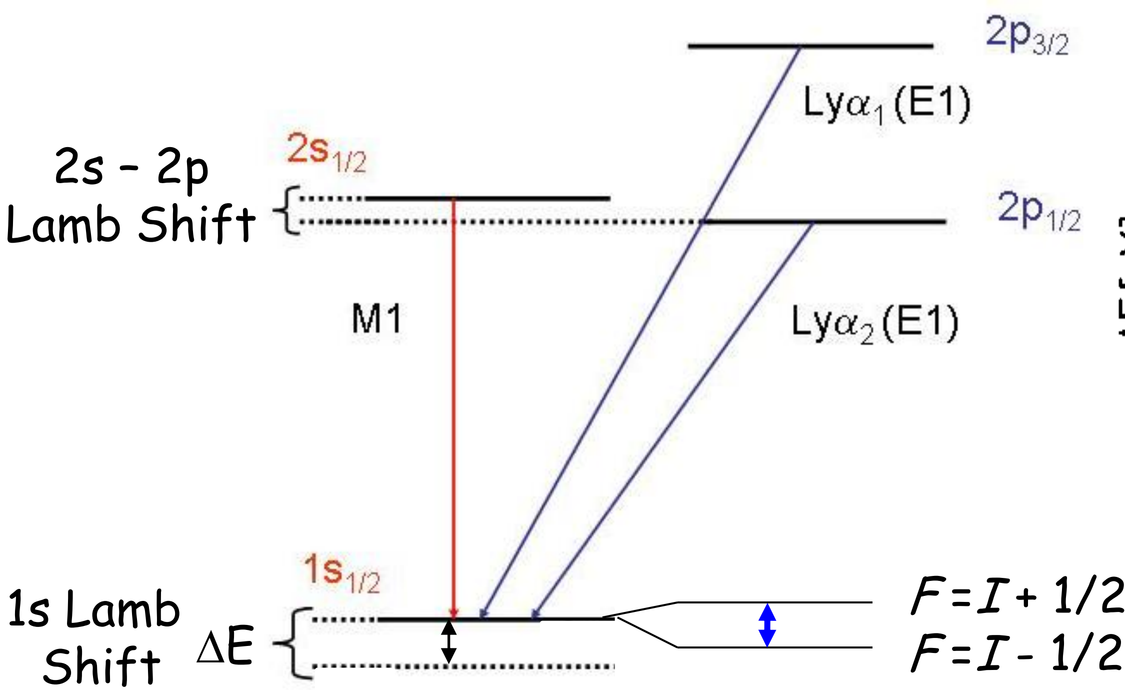


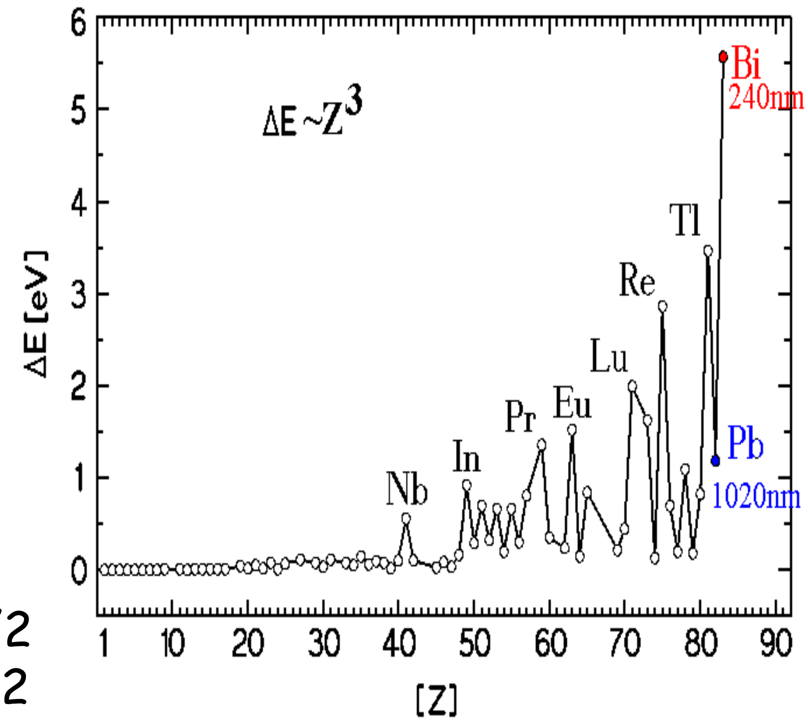
$\Delta E \approx 500$ eV
$Z \cdot \alpha \approx 1$

Quantum
Electro-
Dynamics

$\Delta E \approx 10^{-6}$ eV
$Z \cdot \alpha \approx 10^{-2}$

Hydrogen-like systems: Hyperfine Transitions



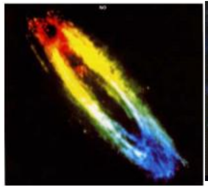


	H		$^{209}Bi^{82+}$
	λ = 21 cm	→	λ = 243.9 nm
	$\tau \approx 1.1 \times 10^7$ a	→	$\tau \approx 400\ \mu s$

Hyperfine (M1) Transitions:

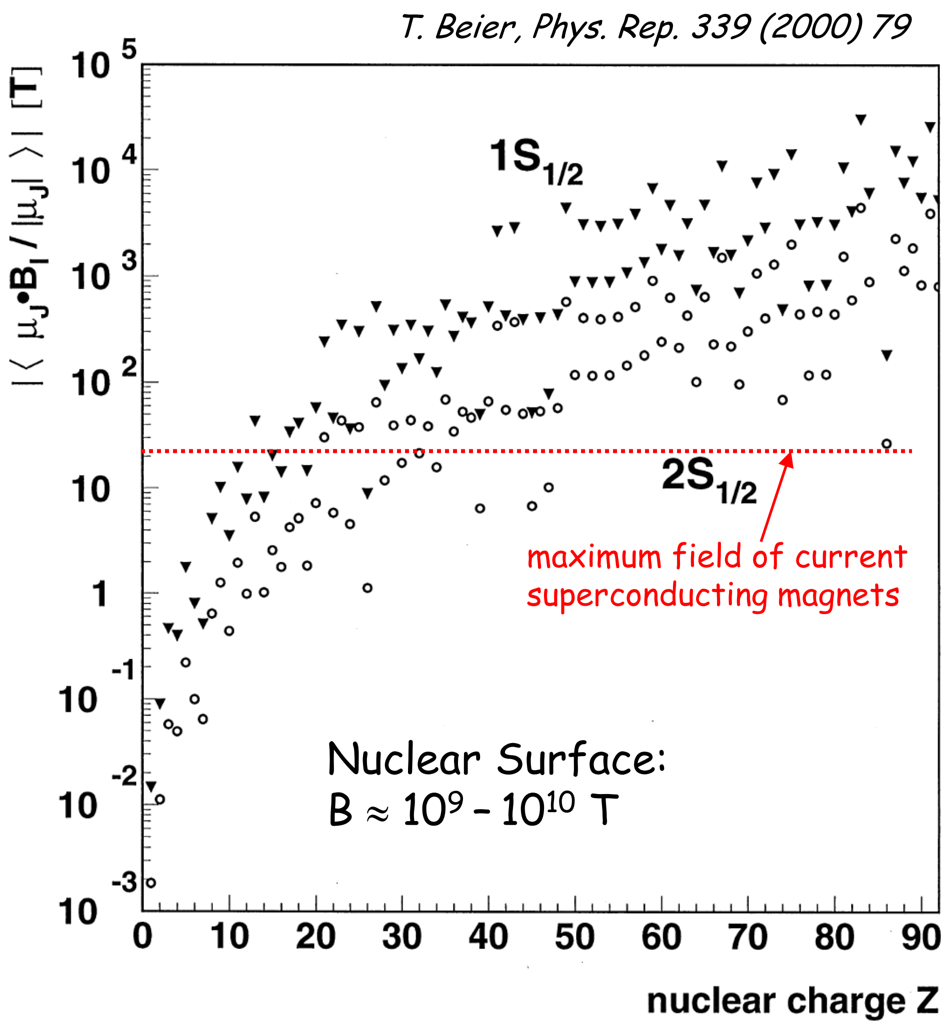
$\nu \sim Z^3$

$\tau \sim (\Delta E)^{-3} \sim Z^{-9}$



Why Hyperfine Structure Transitions ?

Magnetic Field Strength



Hyperfine Structure probes extremely strong magnetic fields very close to the nuclear surface.

Hyperfine Structure of Highly Charged Ions

$$\Delta E_{\rm HFS} = \underbrace{\alpha g_I \frac{m_e}{m_p} \frac{F(F+1) - I(I+1) - j(j+1)}{2j(j+1)} m_e c^2 \frac{(Z\alpha)^3}{n^3(2l+1)}}_{\text{Non-Relativistic Result}} \underbrace{A(Z\alpha)}_{\text{Relativistic Correction}}$$

$$E_{1s_{1/2}} = \lambda$$

$$A_{1s_{1/2}}(Z\alpha) = \frac{1}{\lambda(2\lambda - 1)}$$

$$= 1 + \frac{3}{2}(Z\alpha)^2 + \frac{17}{8}(Z\alpha)^4 + \cdots$$

Including Nuclear Structure and QED Contributions:

$$\Delta E_{\rm HFS} = \alpha g_I \frac{m_e}{m_p} \frac{F(F+1) - I(I+1) - j(j+1)}{2j(j+1)} m_e c^2$$

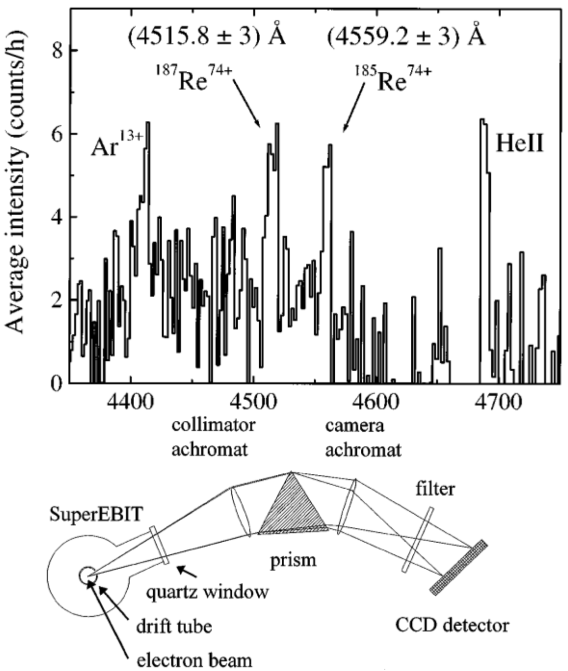
$$\times \frac{(Z\alpha)^3}{n^3(2l+1)} \mathscr{M} \left[A(Z\alpha)(1-\delta)(1-\varepsilon) + \left(\frac{\alpha}{\pi}\right) \Delta\mathscr{E}_{\rm QED} \right].$$

- $\mathscr{M}$: Nuclear Mass Effect
- $A(Z\alpha)$: Relativistic Effects
- $(1-\delta)$: Breit-Rosenthal Effect
- $(1-\varepsilon)$: Bohr-Weisskopf Effect
- $\left(\frac{\alpha}{\pi}\right)\Delta\mathscr{E}_{\rm QED}$: QED Contribution

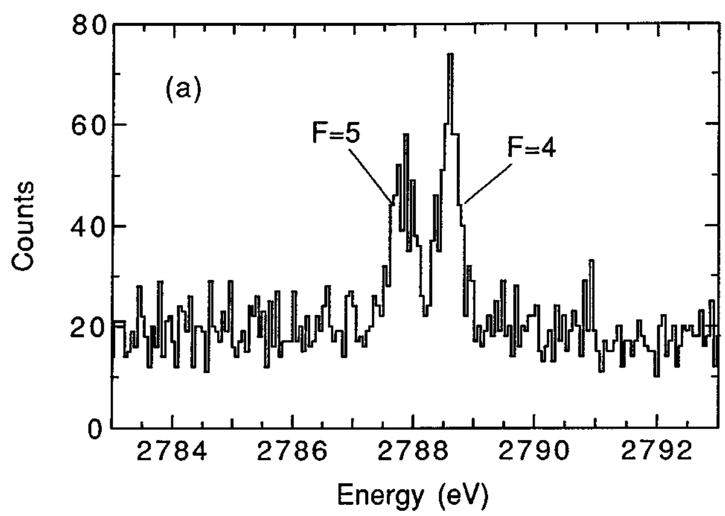
M1-Spectroscopy on Hydrogen-like Ions

Species	λ (nm)	Transition	Type and reference
$^{165}Ho^{66+}$	572.64(1.5)	$F = 4 \rightarrow F = 3$	EBIT [60]
$^{185}Re^{74+}$	456.05(3)	$F = 3 \rightarrow F = 2$	EBIT [61]
$^{187}Re^{74+}$	451.69(5)	$F = 3 \rightarrow F = 2$	EBIT [61]
$^{203}Tl^{80+}$	385.822(30)	$F = 1 \rightarrow F = 0$	EBIT [8]
$^{205}Tl^{80+}$	382.184(34)	$F = 1 \rightarrow F = 0$	EBIT [8]
$^{207}Pb^{81+}$	1019.7(2)	$F = 1 \rightarrow F = 0$	RING [7]
$^{207}Pb^{81+}$	1019.5(2)	$F = 1 \rightarrow F = 0$	RING [62]
$^{209}Bi^{82+}$	243.87(4)	$F = 5 \rightarrow F = 4$	RING [6]
$^{209}Bi^{82+}$	243.87(2)	$F = 5 \rightarrow F = 4$	RING [62]
$^{209}Bi^{80+}$	1511(48)	$F = 5 \rightarrow F = 4$	EBIT [63]
$^{209}Bi^{80+}$	1566(10)	$F = 5 \rightarrow F = 4$	EBIT [64]

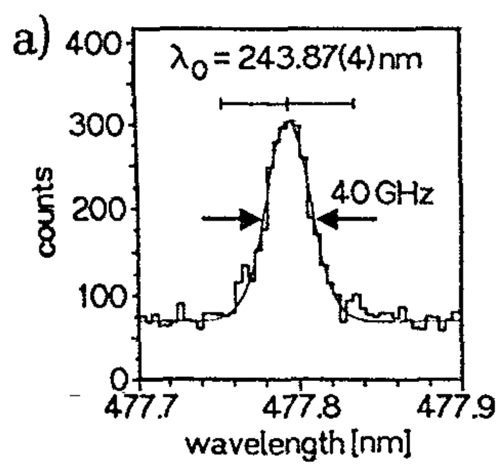
Direct Observation of M1 Fluorescence



Difference between X-Ray Transitions



Laser Spectroscopy



Disentangling QED and nuclear structure

H-like:

$$\Delta E^{(1s)} = \Delta E^{(1s)}_{\text{Dirac}}(1 - \varepsilon^{(1s)}) + \Delta E^{(1s)}_{\text{QED}} ,$$

Li-like:

$$\Delta E^{(2s)} = \Delta E^{(2s)}_{\text{Dirac}}(1 - \varepsilon^{(2s)}) + \Delta E_{\text{int}}(1 - \varepsilon^{(\text{int})}) + \Delta E^{(2s)}_{\text{QED}} + \Delta E_{\text{int-QED}} .$$

It can be shown that the ratios

$$\frac{\varepsilon^{(2s)}}{\varepsilon^{(1s)}} = f(\alpha Z)$$

and

$$\frac{\varepsilon^{(\text{int})}}{\varepsilon^{(2s)}} = f_{\text{int}}(\alpha Z) .$$

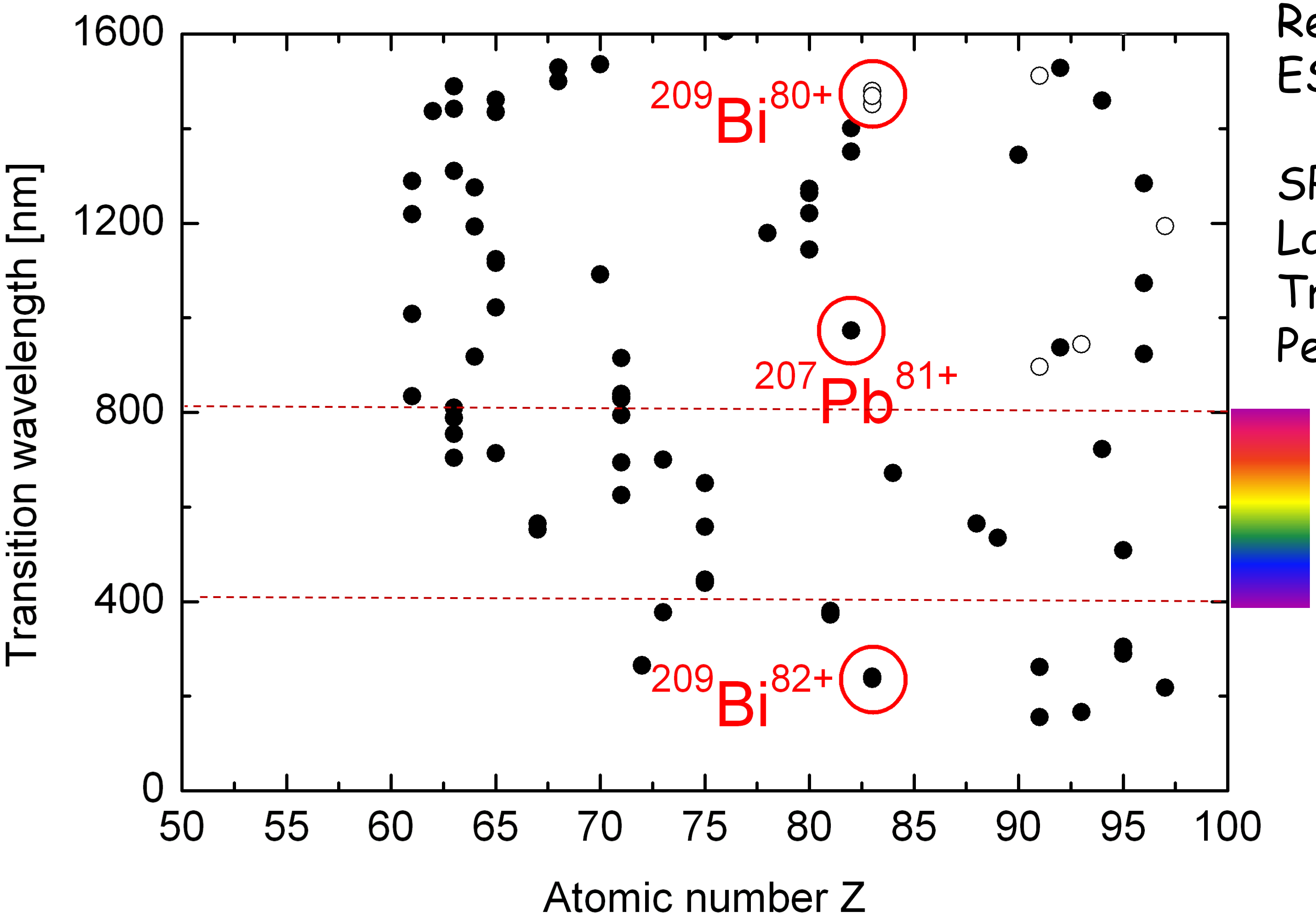
can be calculated to rather high accuracy and is almost independent of the nuclear structure ⇒ Bohr-Weisskopf effect cancels !

↓

Knowing the hyperfine splitting in the H-like ion, the HFS in the Li-like ion can be predicted with high accuracy!

Shabaev *et al.*, PRL **86** 3959 (2001)

Candidates for Spectroscopy

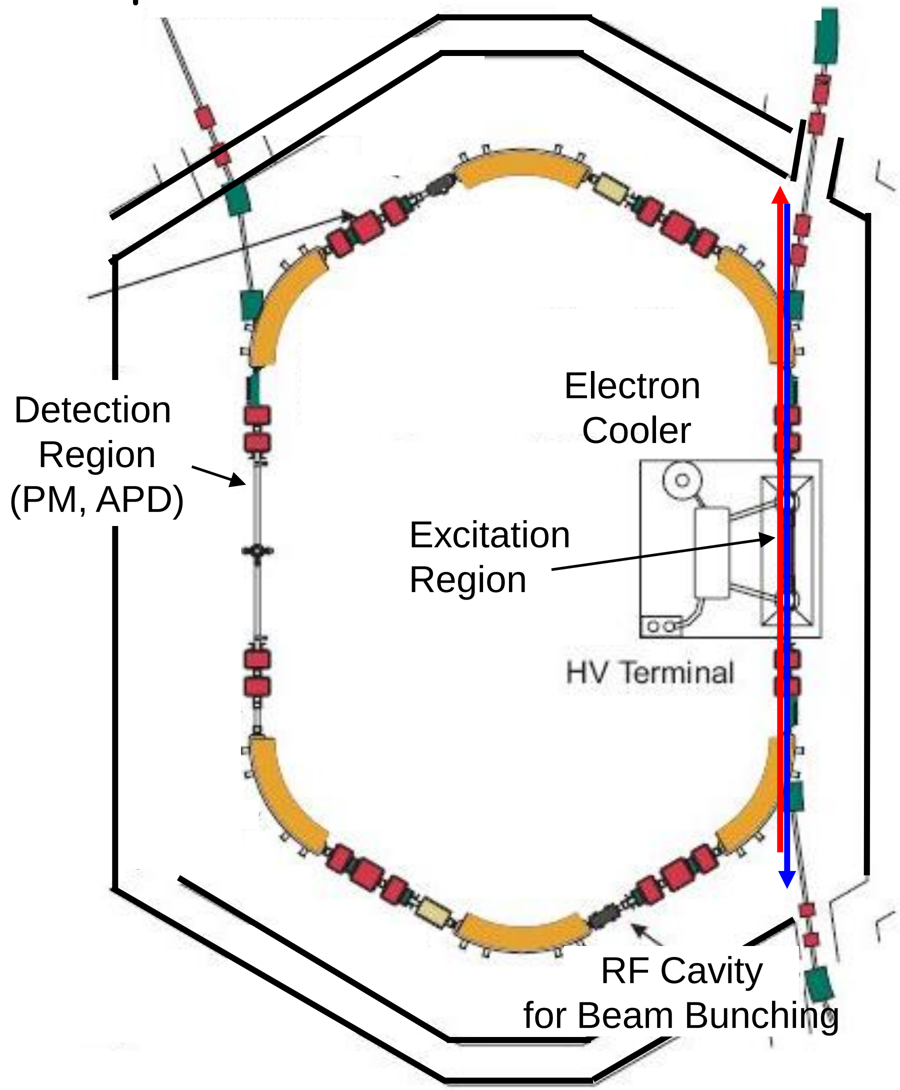


E083:
Relativistic Ions at the ESR

SPECTRAP @ HITRAP:
Laser Spectroscopy on Trapped Ions inside a Penning Trap

ESR: Doppler-Assisted Laser Spectroscopy

Principle:



Doppler Shift:

$$\lambda_{\mathrm{Lab}}^{\uparrow\downarrow} = \lambda_0 \frac{1}{\gamma\ (1+\beta)}$$

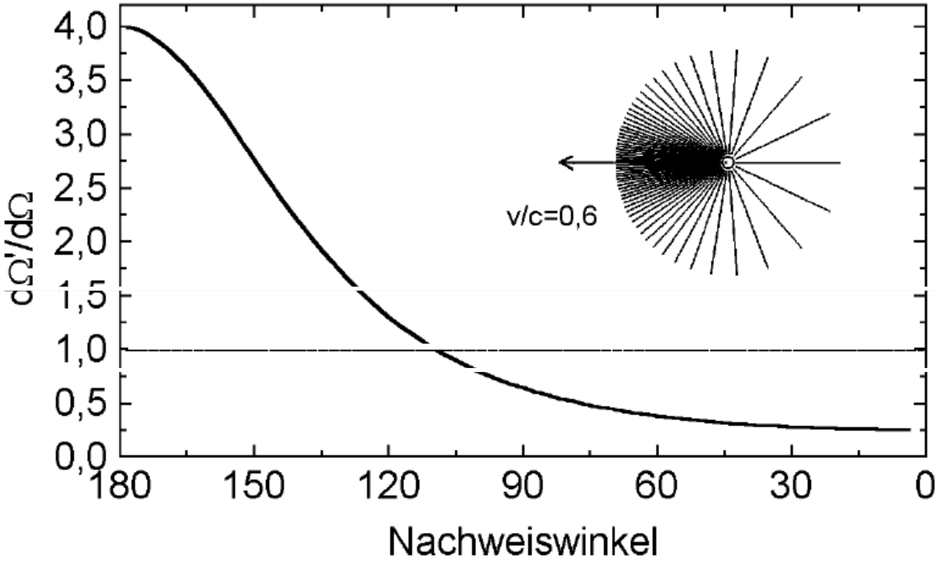
$$\lambda_{\mathrm{Lab}}^{\uparrow\uparrow} = \lambda_0 \frac{1}{\gamma\ (1-\beta)}$$

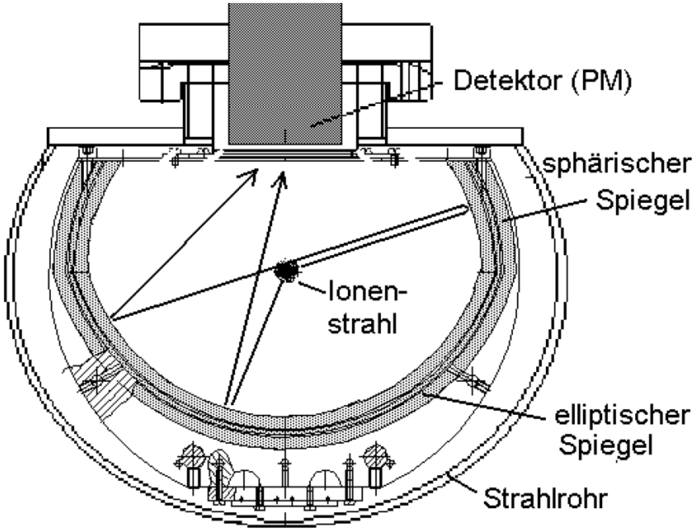
Examples:

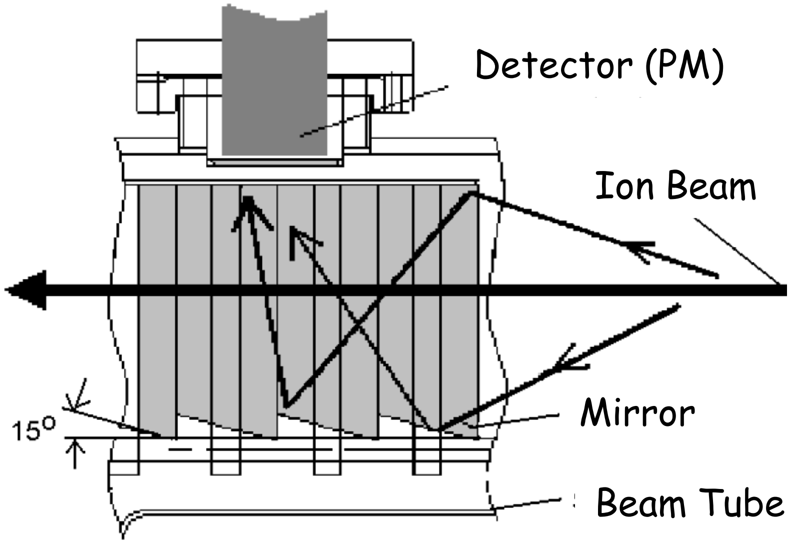
$^{207}Pb^{80+}$: λ_0 = 1020 nm
β = 0.57 (211 MeV/u)
λ_{Lab} = 532 nm

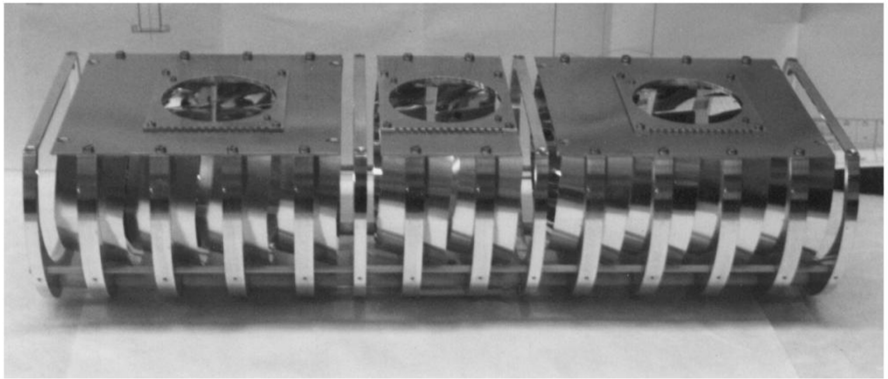
$^{209}Bi^{82+}$: λ_0 = 250 nm
β = 0.59 (218 MeV/u)
λ_{Lab} = 489 nm

Fluorescence Detection at Relativistic Velocities

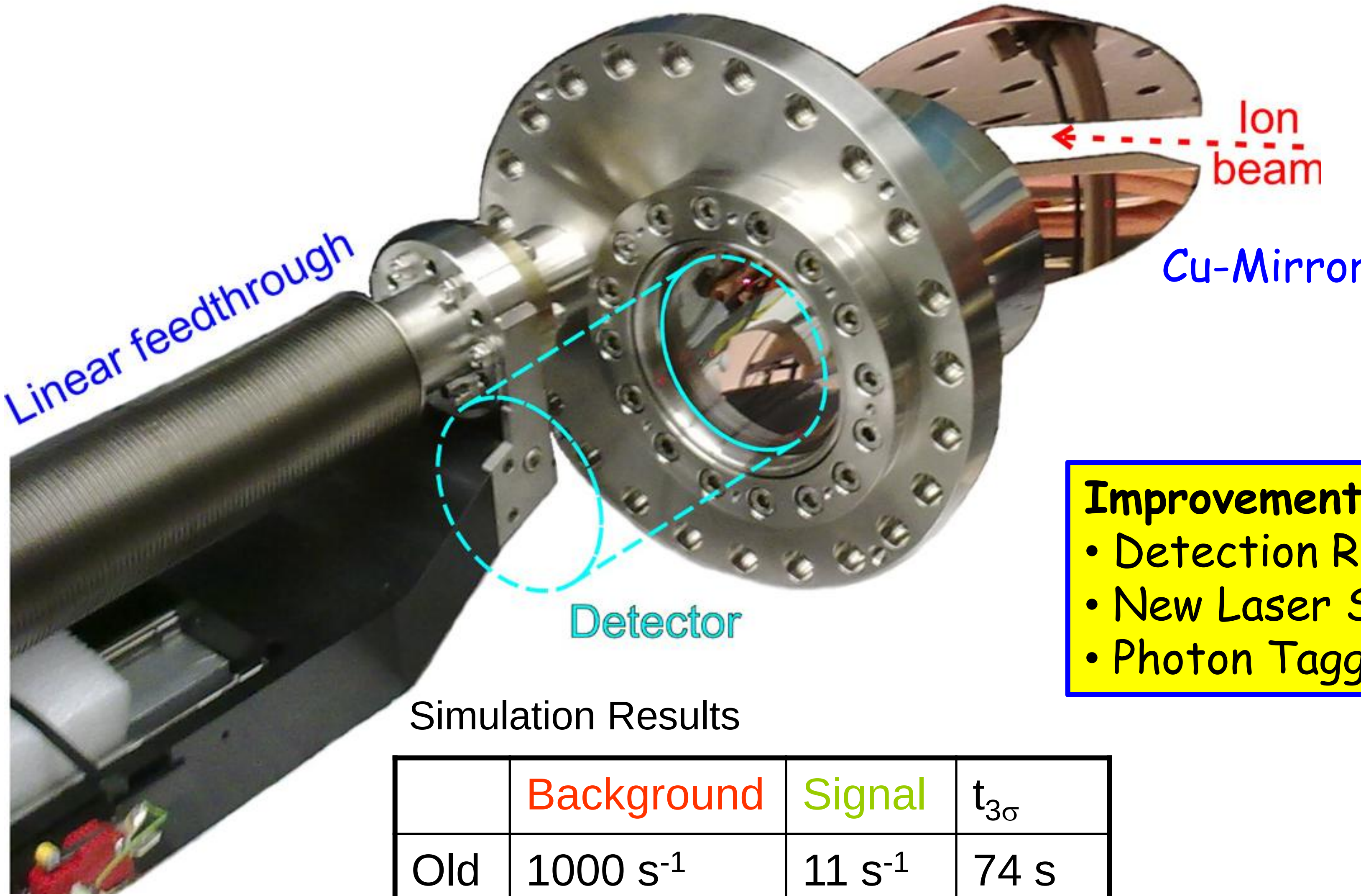








New Detection Device for ESR Spectroscopy



Improvements
- Detection Region
- New Laser System
- Photon Tagging

Simulation Results

	Background	Signal	$t_{3\sigma}$
Old	1000 s^{-1}	11 s^{-1}	74 s
new	160 s^{-1}	45 s^{-1}	0,7 s

The E083 Collaboration (LIBELLE)

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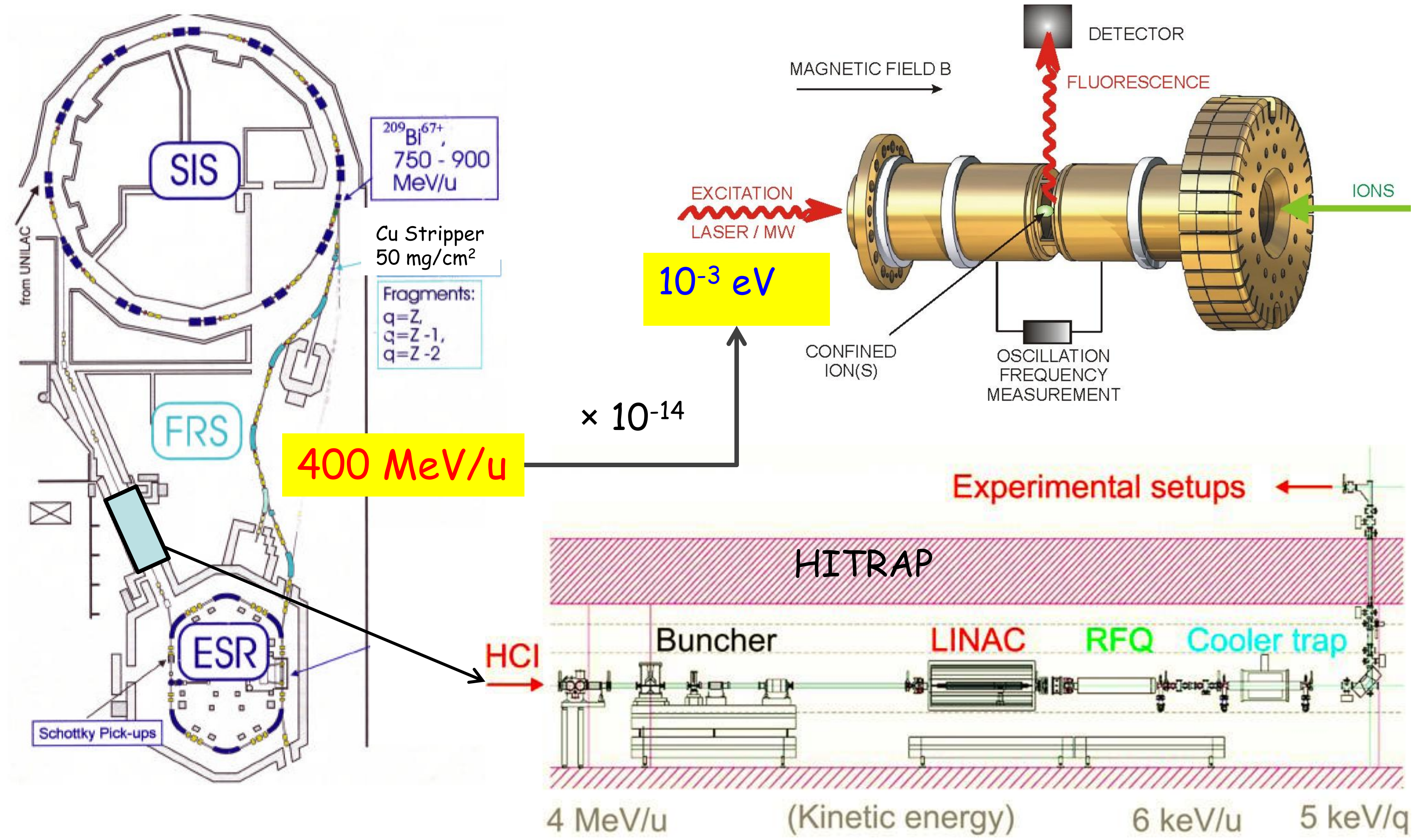
LIBELLE (Dragonfly)

Lithium-like Bismuth Excitation with Laser Light at the ESRcomic

Complementary: Cold Trapped Ions



The SPECTRAP Collaboration

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€ € € € € € € € €
Helmholtz Association,
GSI, BMBF

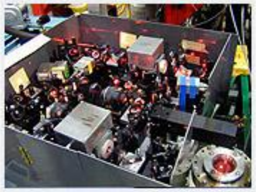
Conclusion

- Atoms are versatile laboratories for a manifold of investigations.
- Many subtle effects leave their trace in the electronic energies.
- Nuclear structure of exotic isotopes can be studied by laser spectroscopy and provide important information for nuclear structure models.
- Studying highly charged ions allows to study QED in the strong-field regime.
- Once understood, these investigations can again be used to study the structure of nuclei in more detail.

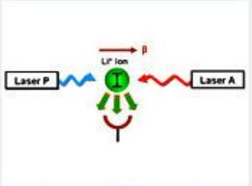
LaserSpHERe

Laser SpHERe

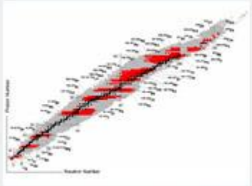
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ



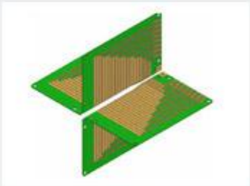
ToPLIS



Test der SRT am ESR



Laserspektroskopie on-line

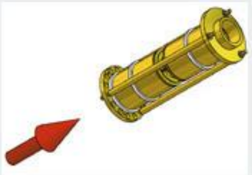


BeTINa

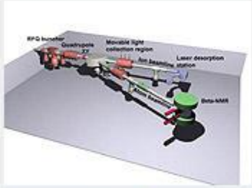
Laser Spektroskopie an

Laser SpHERe

hochgeladenen **I**onen und **e**xotischen **r**adioaktiven Nukli**de**n

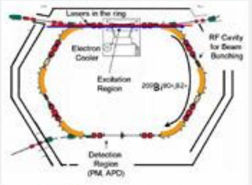


SpecTrap



LaSpec

TRIGA-LASER



Lithiumähnliches Bismut

http://www.uni-mainz.de/FB/Chemie/AK-Noertershaeuser/

Funding :

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Deutsche Forschungsgemeinschaft DFG

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Helmholtz Graduate School for Hadron and Ion Research

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Stiftung Rheinland-Pfalz für Innovation

Carl Zeiss Stiftung