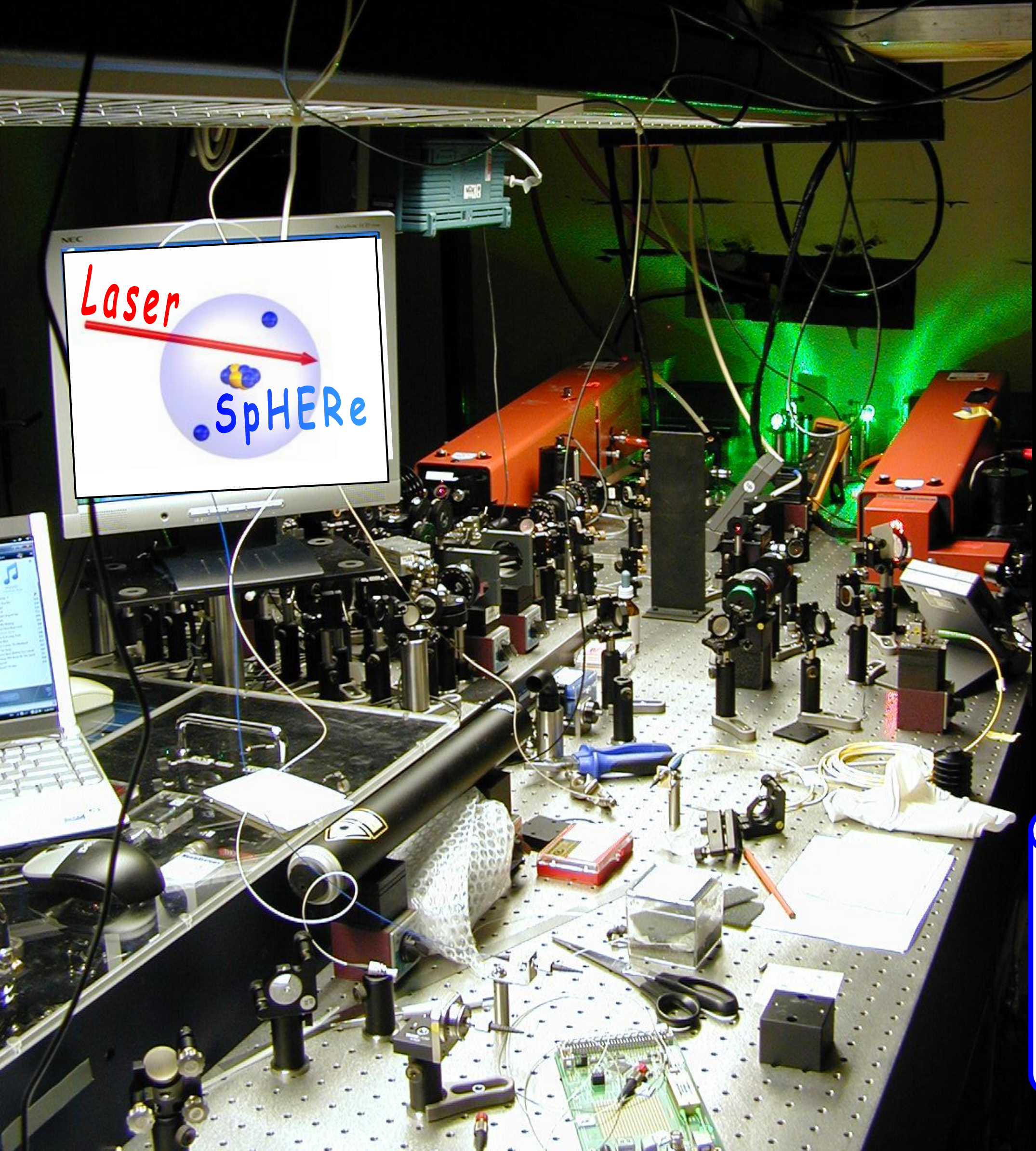
Recent Developments in Collinear Laser Spectroscopy at ISOLDE/CERN



W. Nörtershäuser

for the

Collaps

Collinear Laser Spectroscopy

Collaboration

GSI

HELMHOLTZ GEMEINSCHAFT

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

Anniversaries 2010

50 years of LASERS

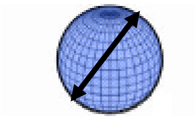
30 years of COLLAPS

Nuclear Ground State Properties Extracted from Optical Spectra

ISOTOPE SHIFT

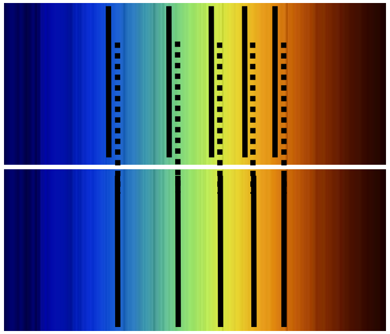
Finite Size Effect

$\Rightarrow$ Change of Charge Radius



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

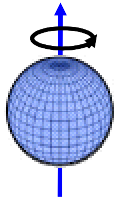
Isotop 1



Isotop 2

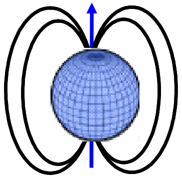
HYPERFINE STRUCTURE

1. Hyperfine Interaction
   $\Rightarrow$ nuclear spin



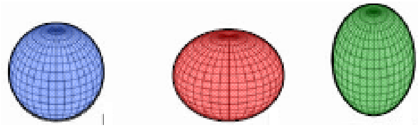
$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$

2. Magnetic Dipole HFS
   $\Rightarrow$ nuclear magnetic moment,
   g-factor $\leftrightarrow$ Parity



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

3. Electric Quadrupole HFS
   $\Rightarrow$ spectroscopic quadrupole moment



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

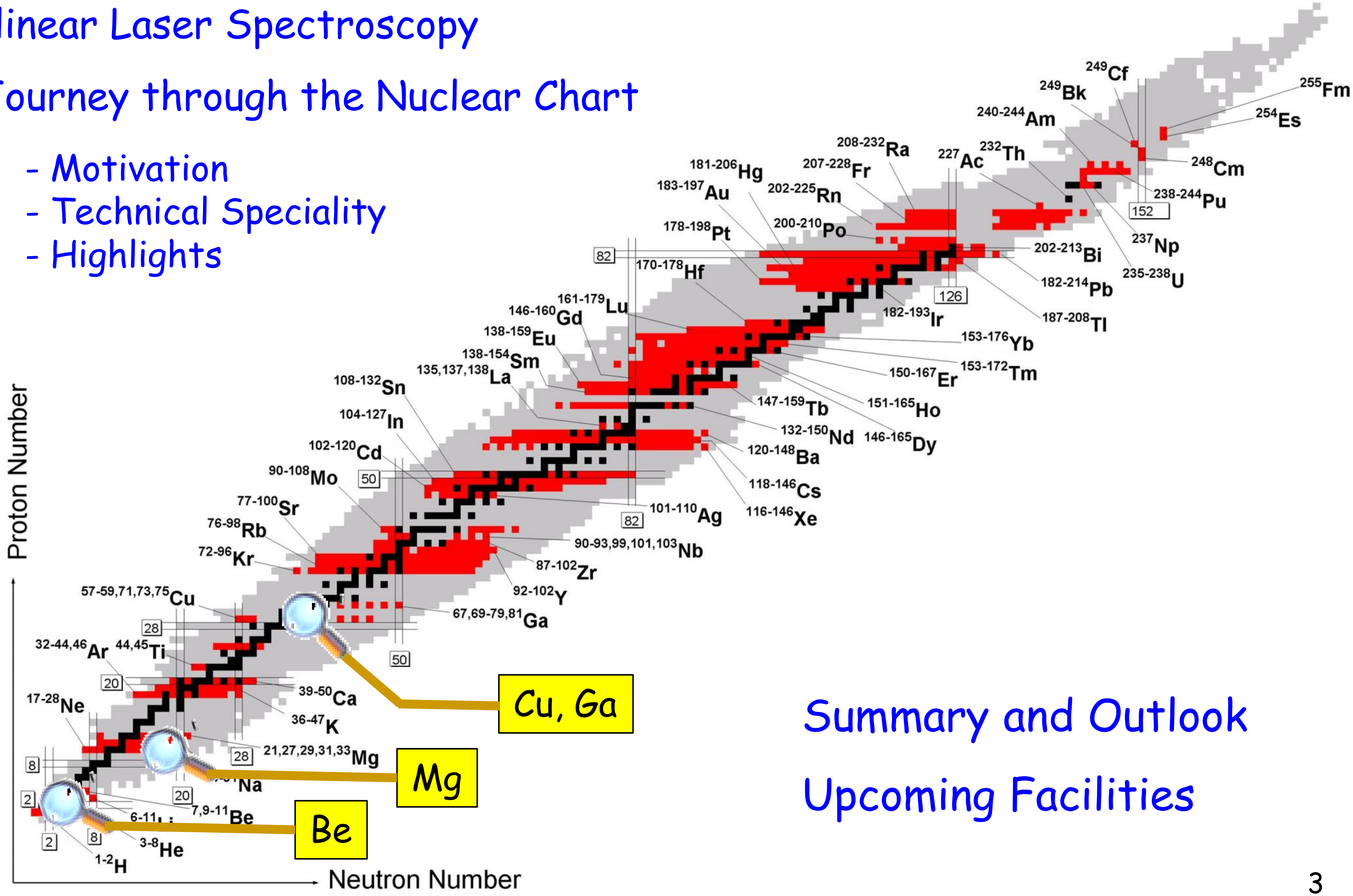
model-independent determination of ground state properties

Outline

Collinear Laser Spectroscopy

A Journey through the Nuclear Chart

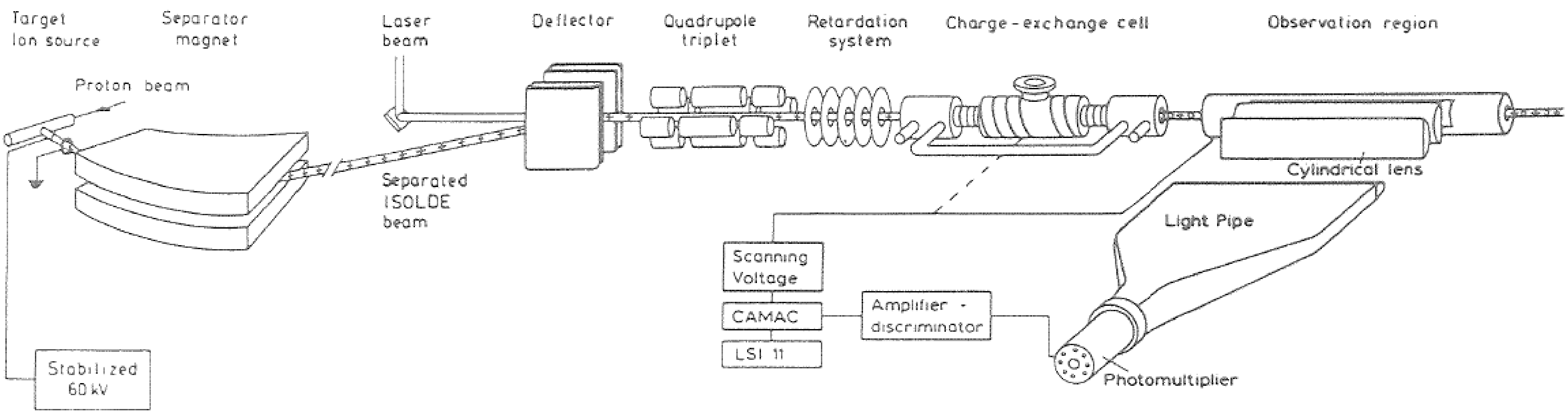
- Motivation
- Technical Speciality
- Highlights



Summary and Outlook

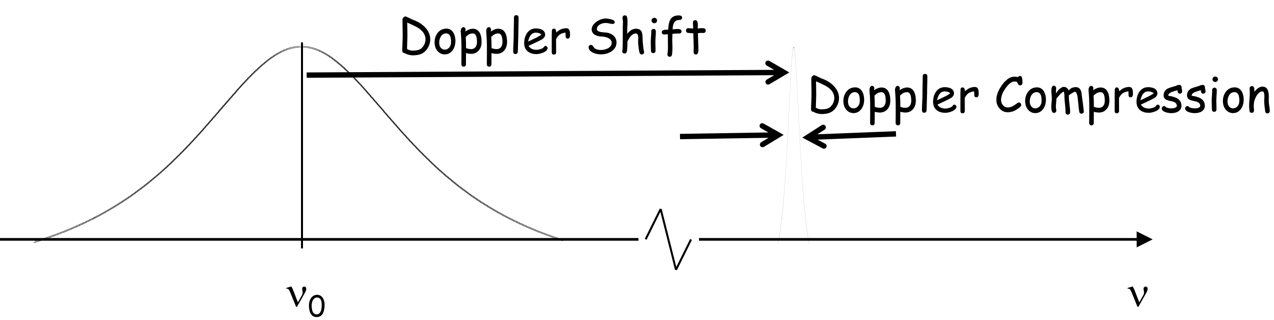
Upcoming Facilities

The Principle of Collinear Laser Spectroscopy

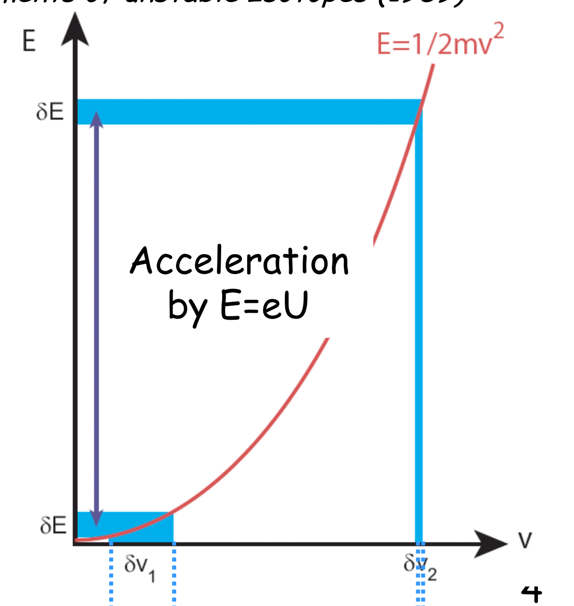


S.L. Kaufman, Opt. Comm. **17** (1976) 309.
T. Meier et al., Opt. Comm. **20** (1977) 397

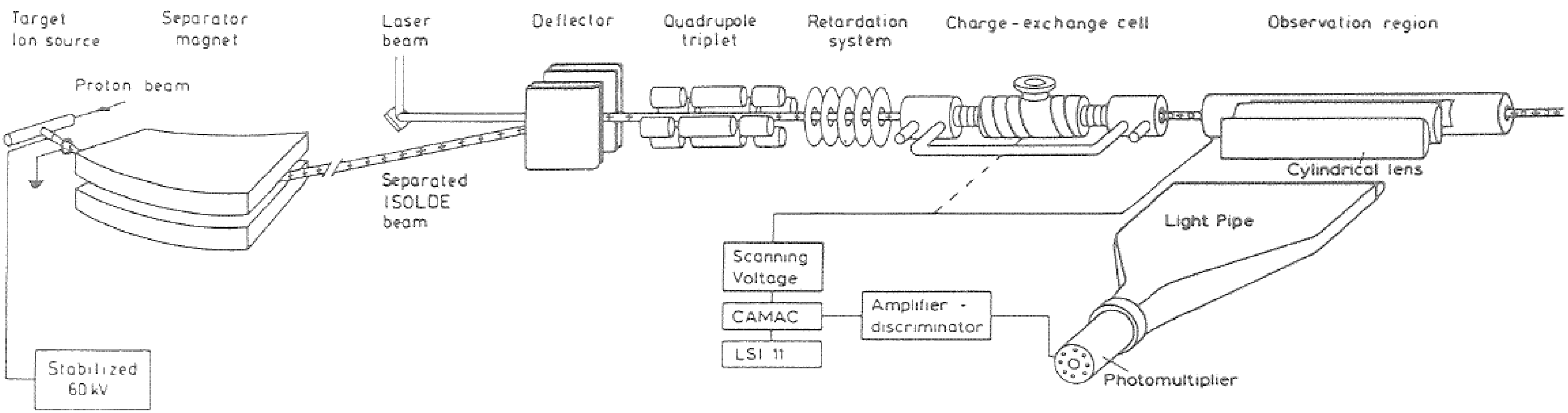
K.-R. Anton, PRL **40** (1978) 642
E.W. Otten, *Nuclear Radii and Moments of unstable Isotopes (1989)*



Doppler width
50-100 MHz



The Principle of Collinear Laser Spectroscopy



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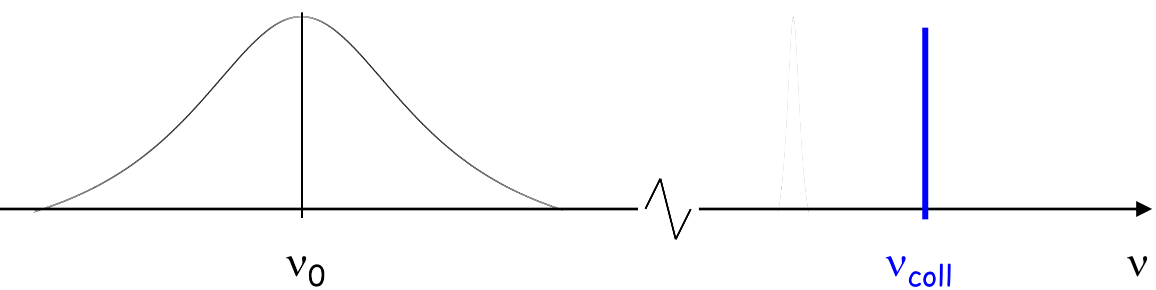


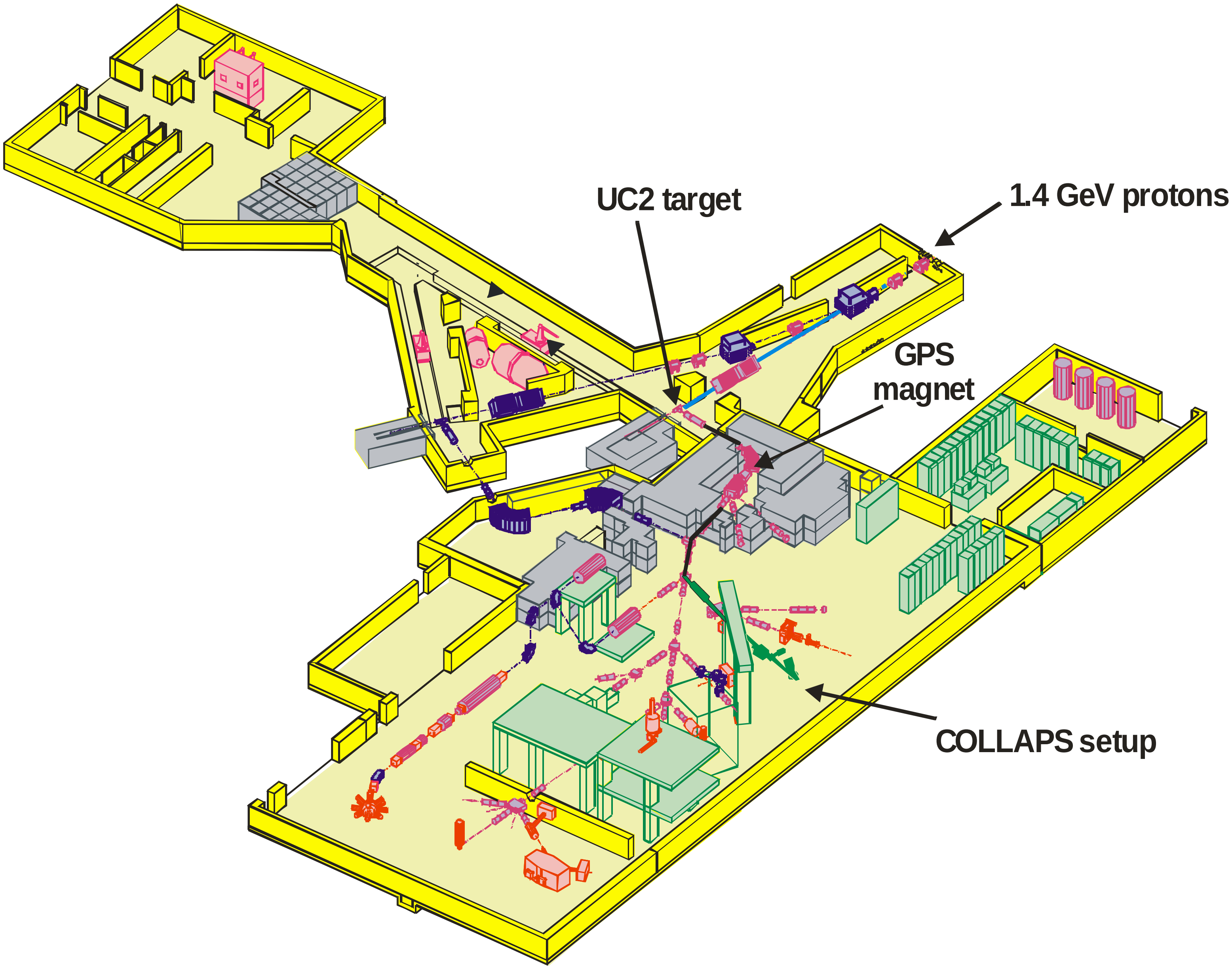
Doppler width
50-100 MHz

Doppler-tuning :

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

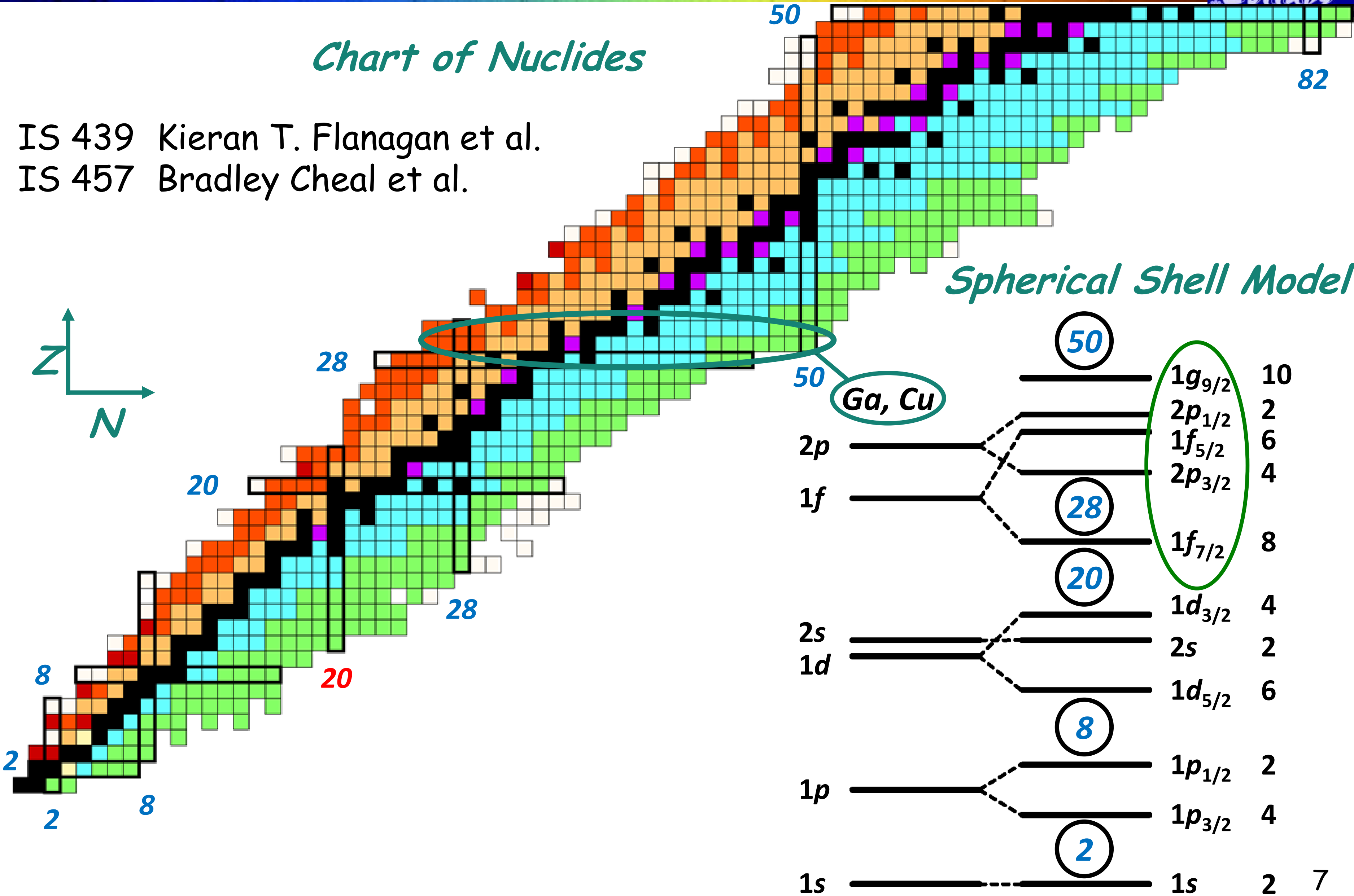
$$\beta = \upsilon/c = \sqrt{2eU/m}$$

COLLAPS at ISOLDE

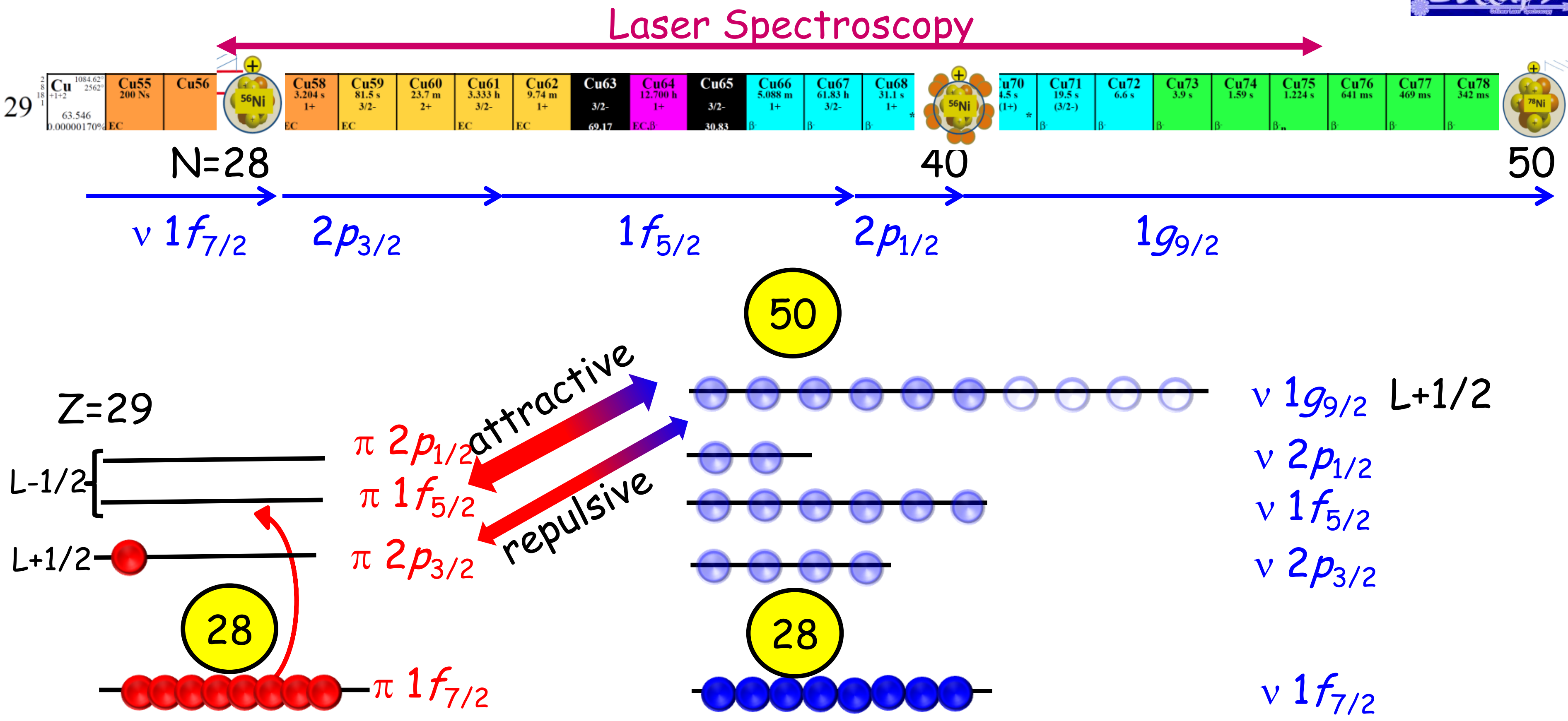


Region 1: Investigating the pfg Shell

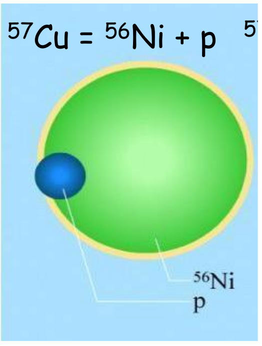
IS 439 Kieran T. Flanagan et al.
IS 457 Bradley Cheal et al.



Copper and Gallium: Stiffness of the ^{58}Ni-Core Evolution in the pfg Shell



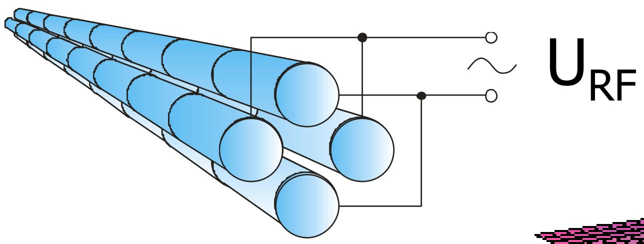
odd-Cu isotopes: ($\pi\ 2p_{3/2}$) $3/2^-$

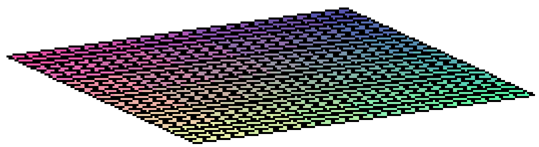


Theory: JUN45: M. Honma et al. PRC 80, 064323 (2009)
jj44b: B.A. Brown (unpublished)

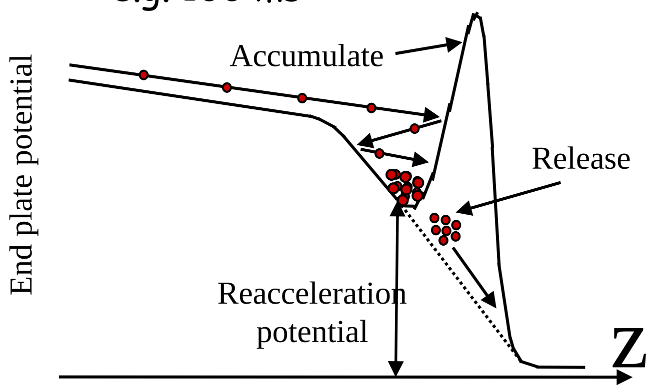
Model space: $(p_{3/2}f_{5/2}p_{1/2}g_{9/2})$

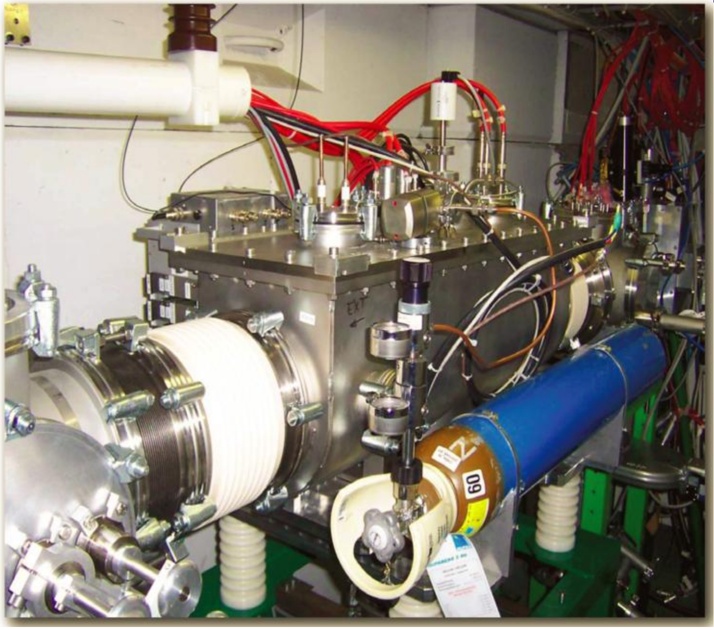
Principle of an RFQ (ISCOOL)



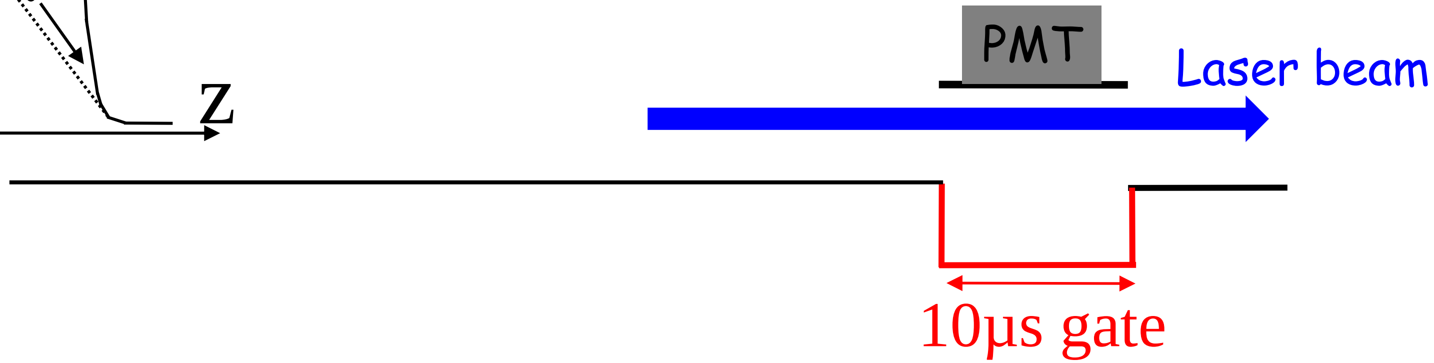


Accumulation for
e.g. 100 ms





E.Mané et al, Eur. Phys. J. A **42**, 503 (2009)

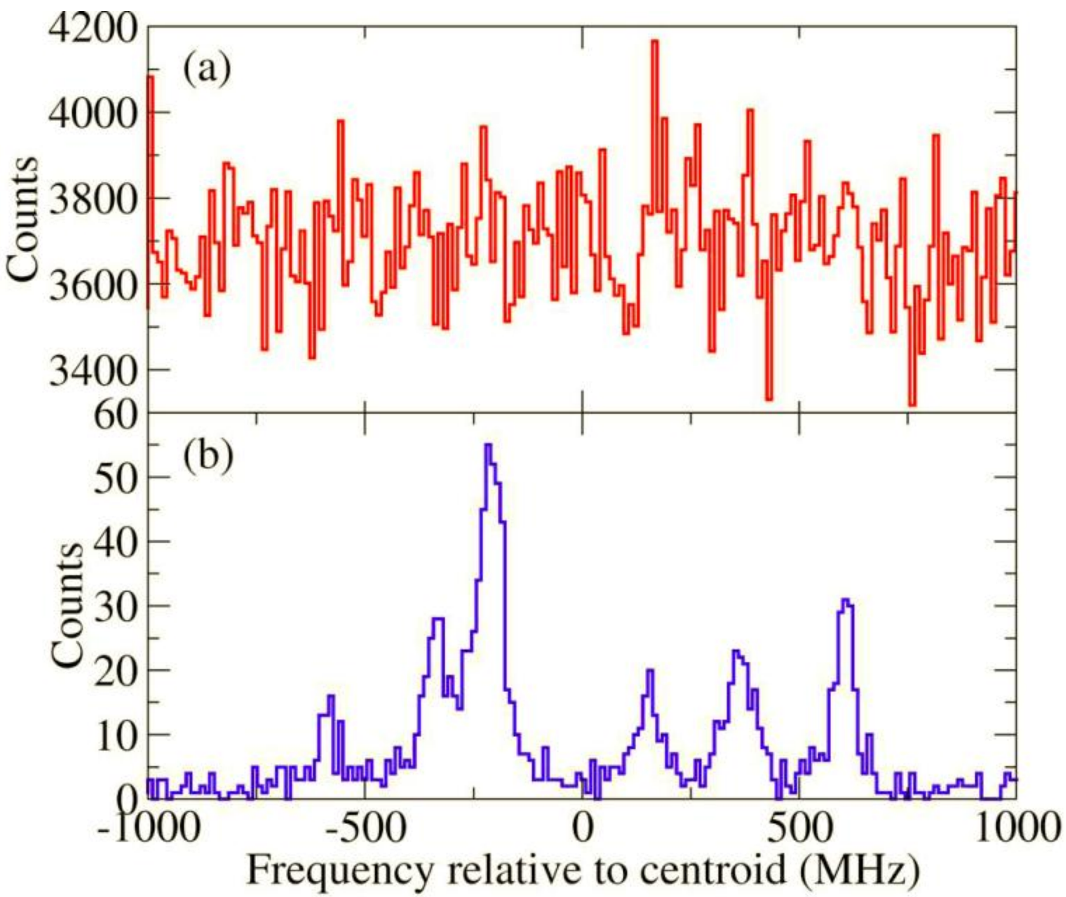


$$\text{Background suppression} = \frac{\text{e.g. 100ms accumulation}}{10\mu\text{s gate width}} \sim 10^4$$

F. Herfurth, NIMA **469**, 254 (2001)
A. Nieminen, Phys. Rev. Lett. **88**, 094801 (2002)

Background Reduction by Bunching

^{76}Ga, Accumulation time: 50 ms



Ungated Spectrum

Gated in Range (64-70 μs)

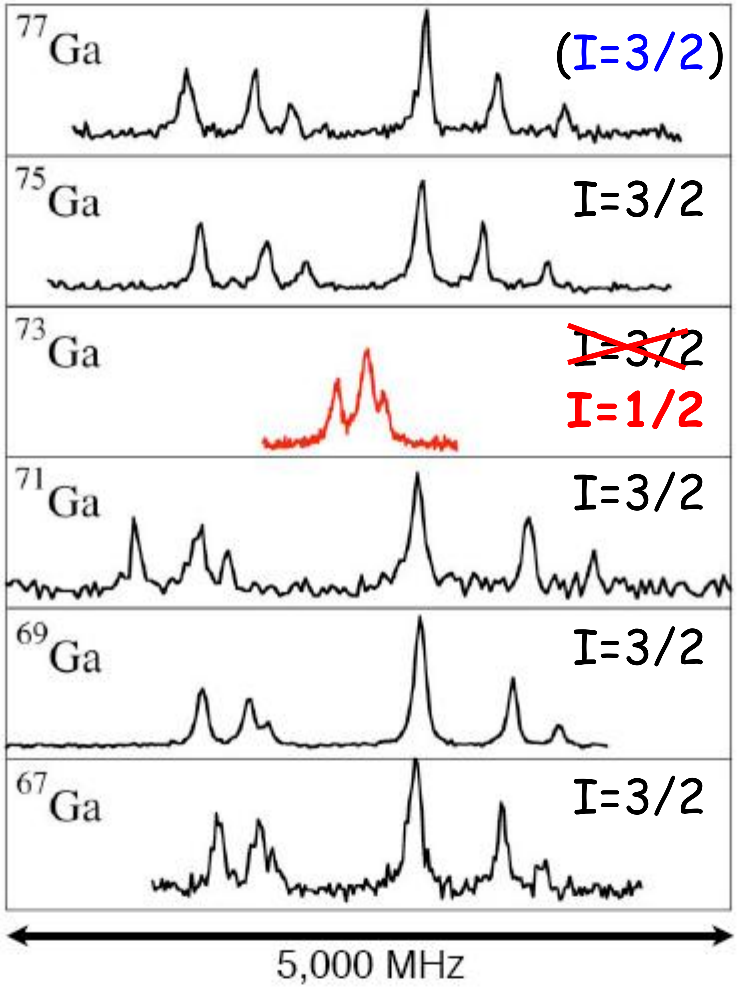
Background Reduction:
$50\text{ ms} / 6\ \mu s \approx 10^4$

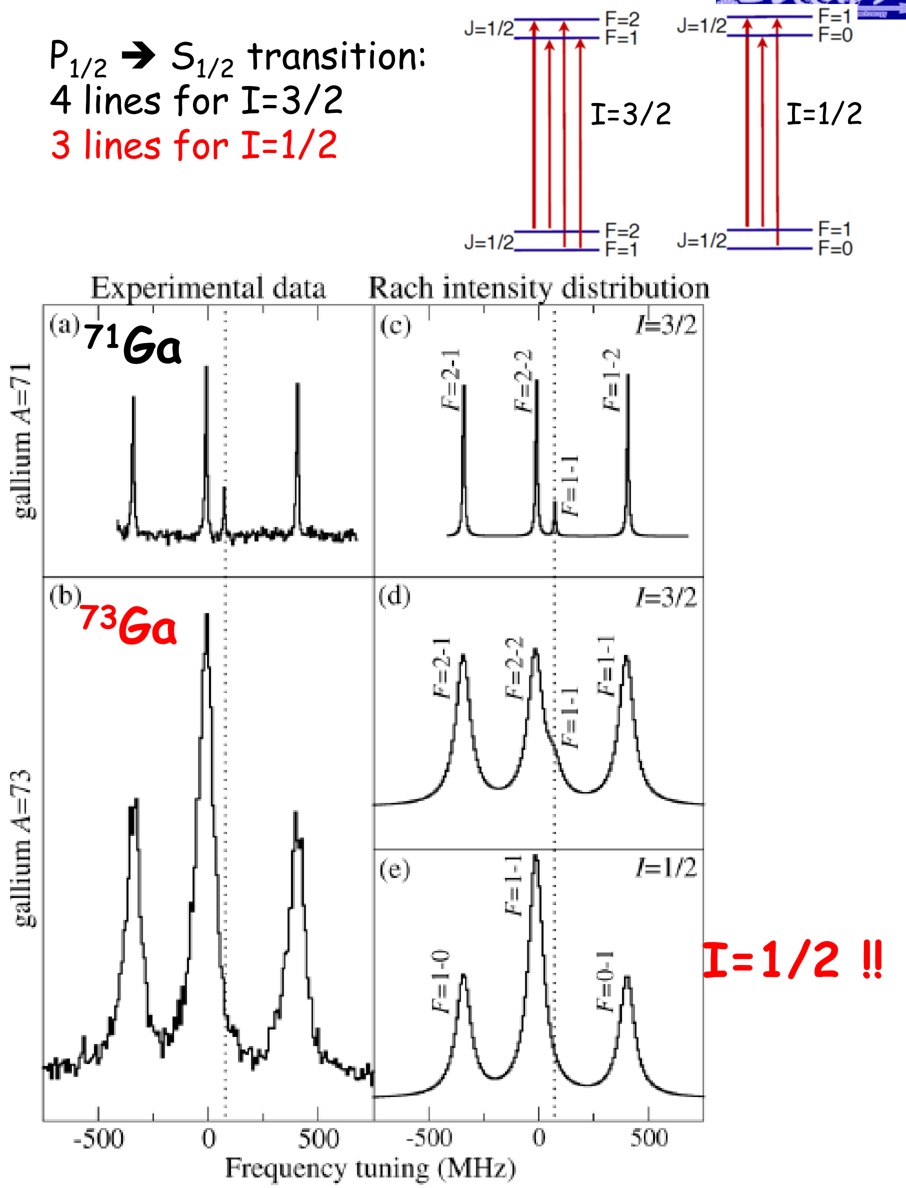
E.Mané, PhD Thesis, University of Manchester

Spin of ^{73}Ga

$P_{3/2} \rightarrow S_{1/2}$ transition:
6 lines for I=3/2
3 lines for I=1/2

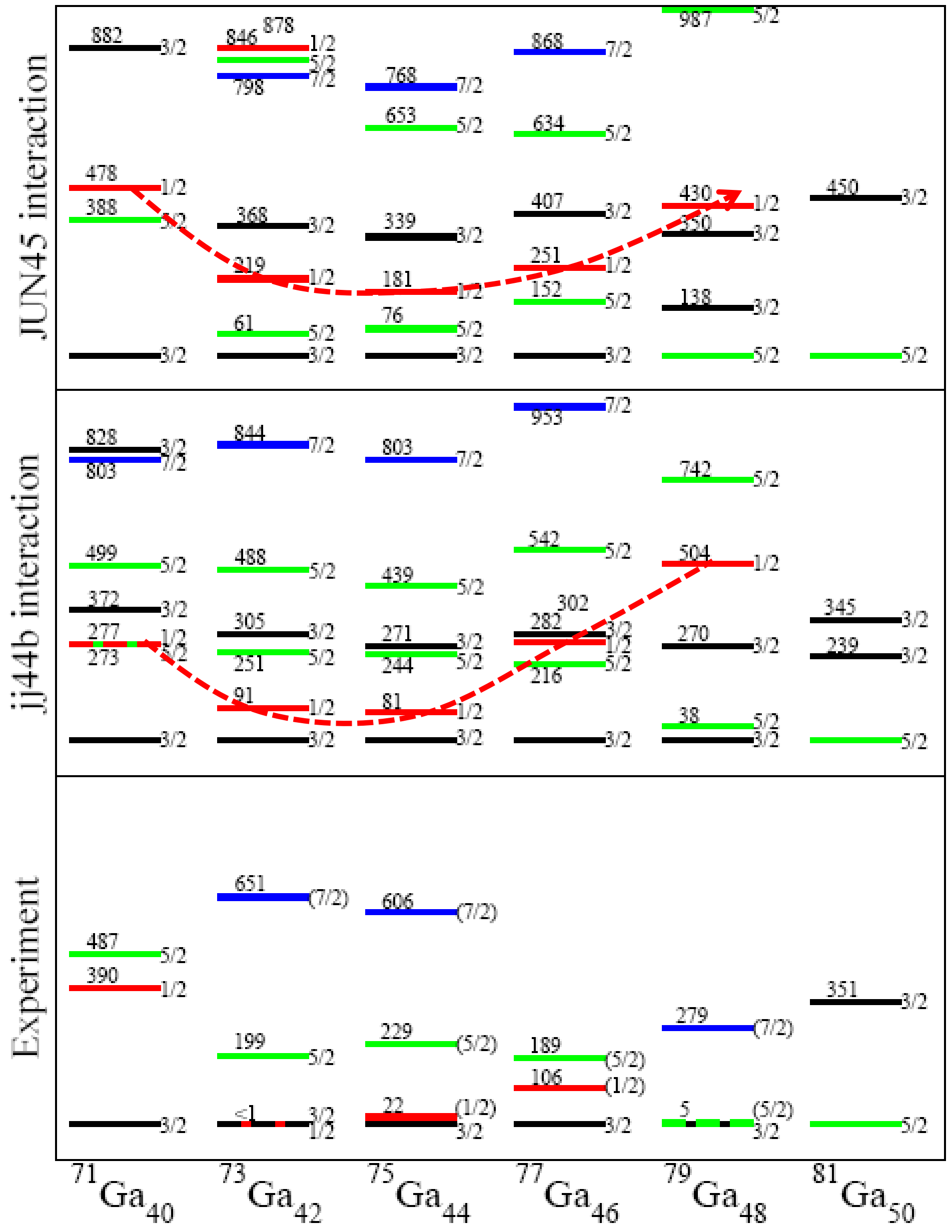
$P_{1/2} \rightarrow S_{1/2}$ transition:
4 lines for I=3/2
3 lines for I=1/2





B. Cheal *et al.*, Phys Rev Lett **104**, 252502 (2009)

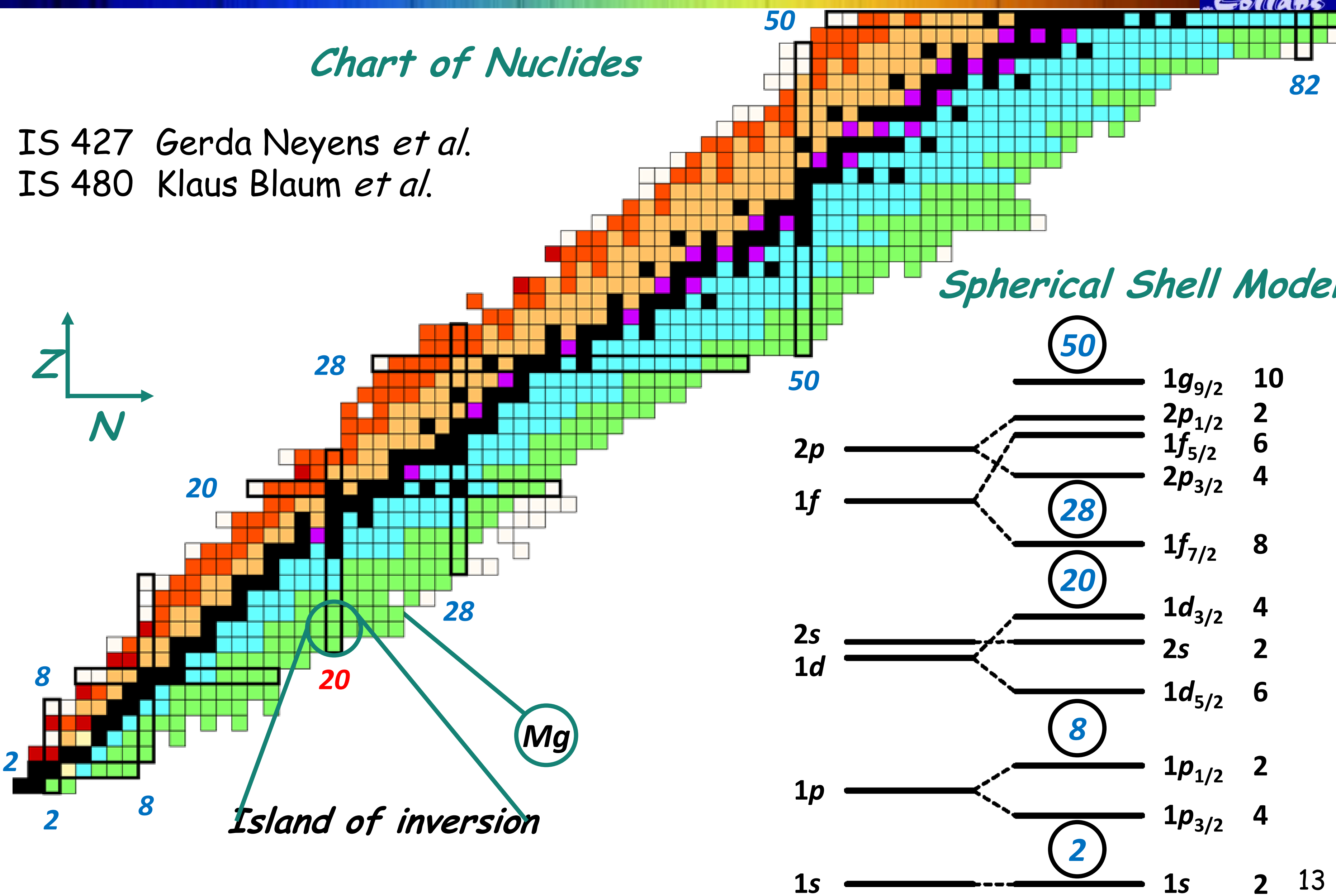
Experimental Levels compared to JUN45 and jj4b



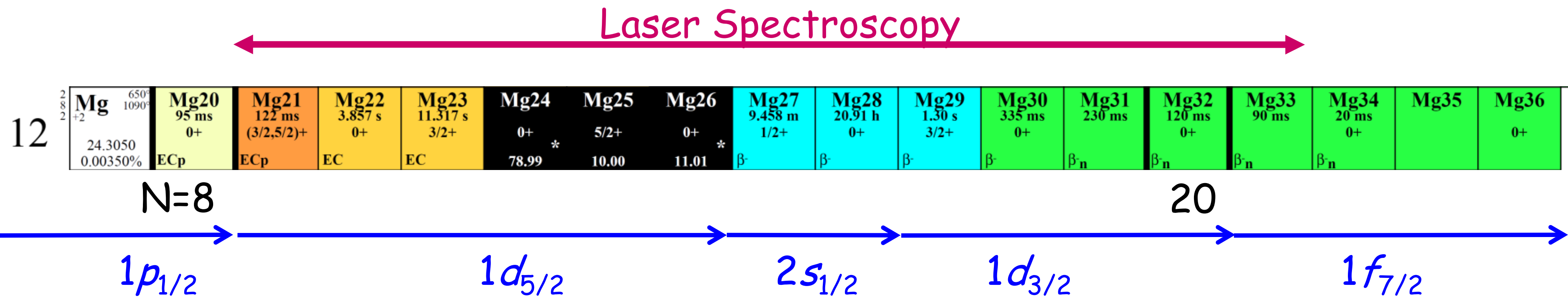
B. Cheal *et al.*, Phys Rev Lett **104**, 252502 (2009)

Region 2:
The sd-Shell and the „Island of Inversion“

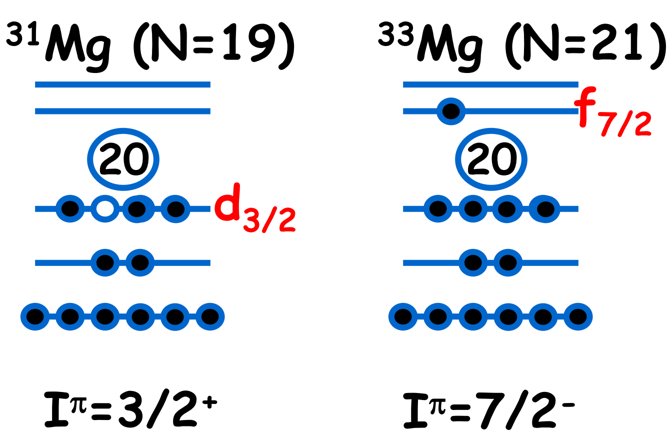
IS 427 Gerda Neyens *et al.*
IS 480 Klaus Blaum *et al.*



Ground-State Spins and Moments

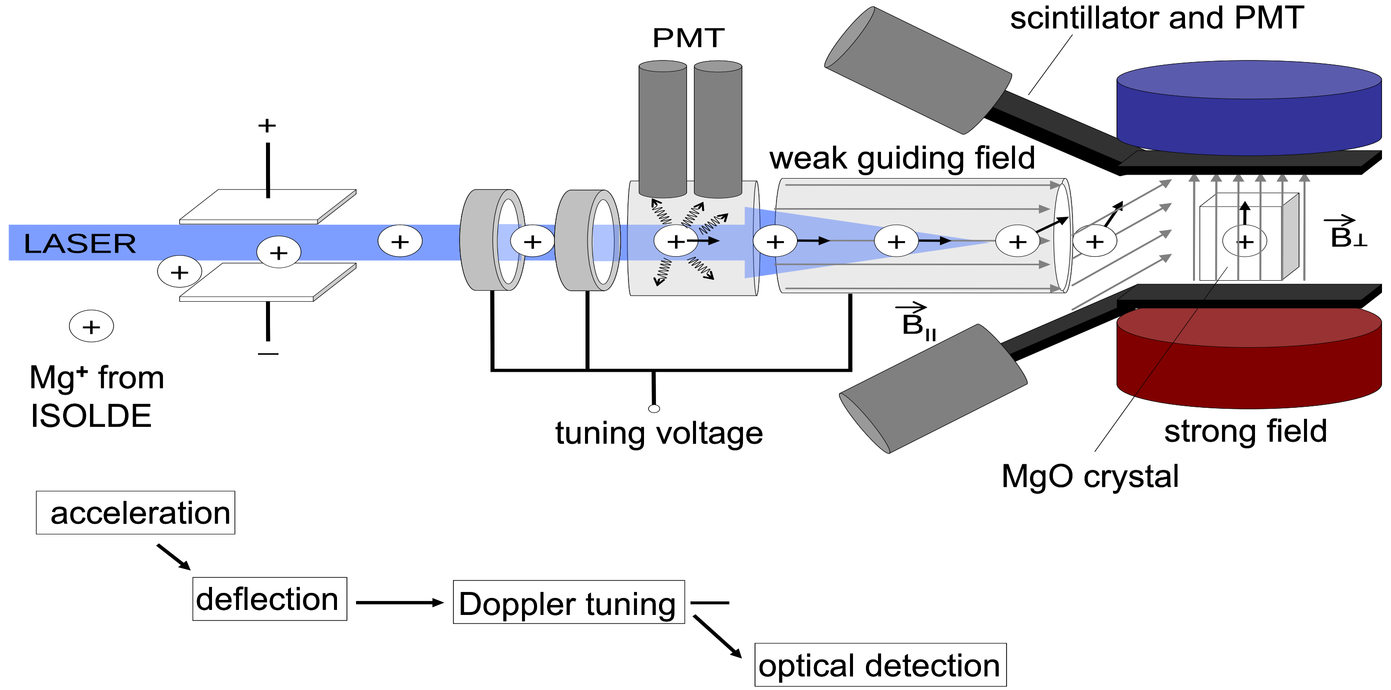


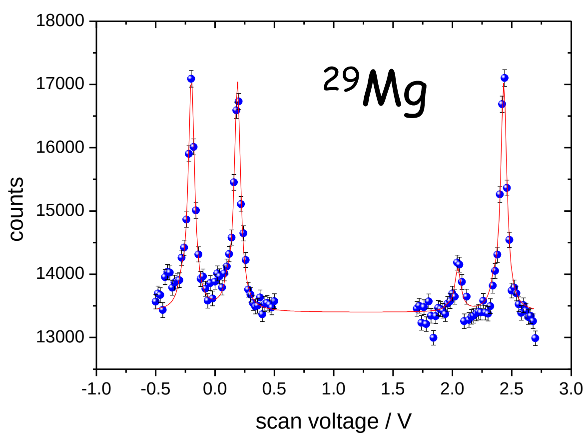
Normal ground state configurations:

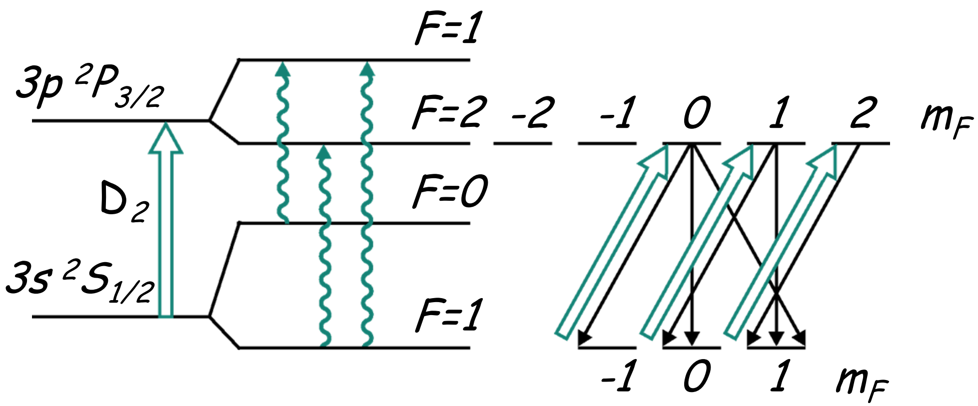


^{21}Mg	3 x10^{3} ions/μC
^{29}Mg	1.2 x10^{6} ions/μC
^{30}Mg	4.6 x10^{5} ions/μC
^{31}Mg	1.5 x10^{5} ions/μC
^{32}Mg	4.2 x10^{4} ions/μC
^{33}Mg	5.3 x10^{3} ions/μC

Optical Pumping and β-NMR







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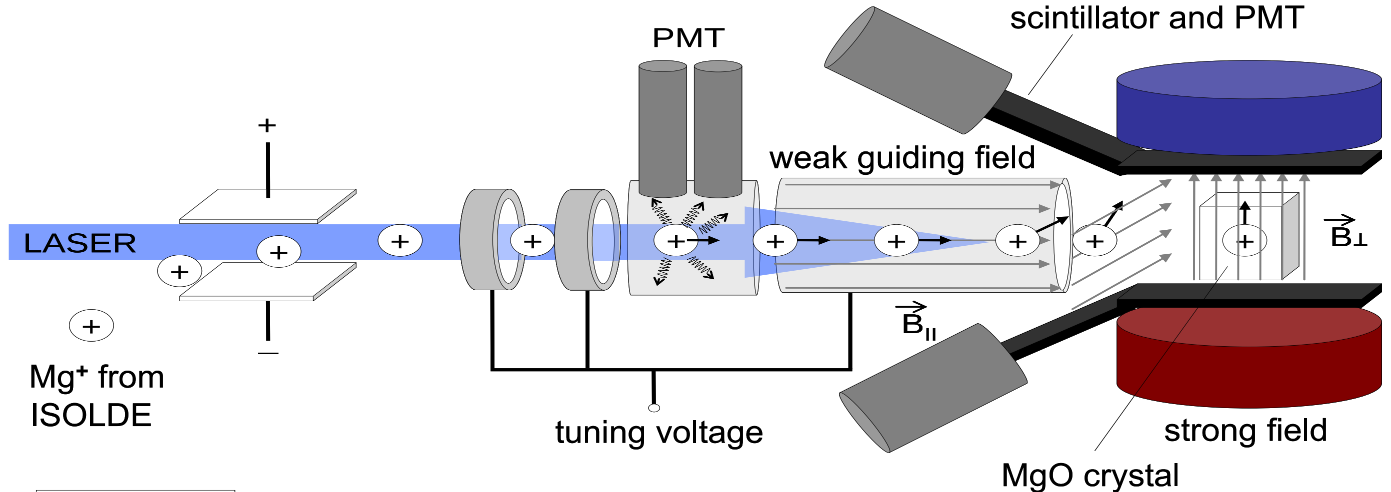
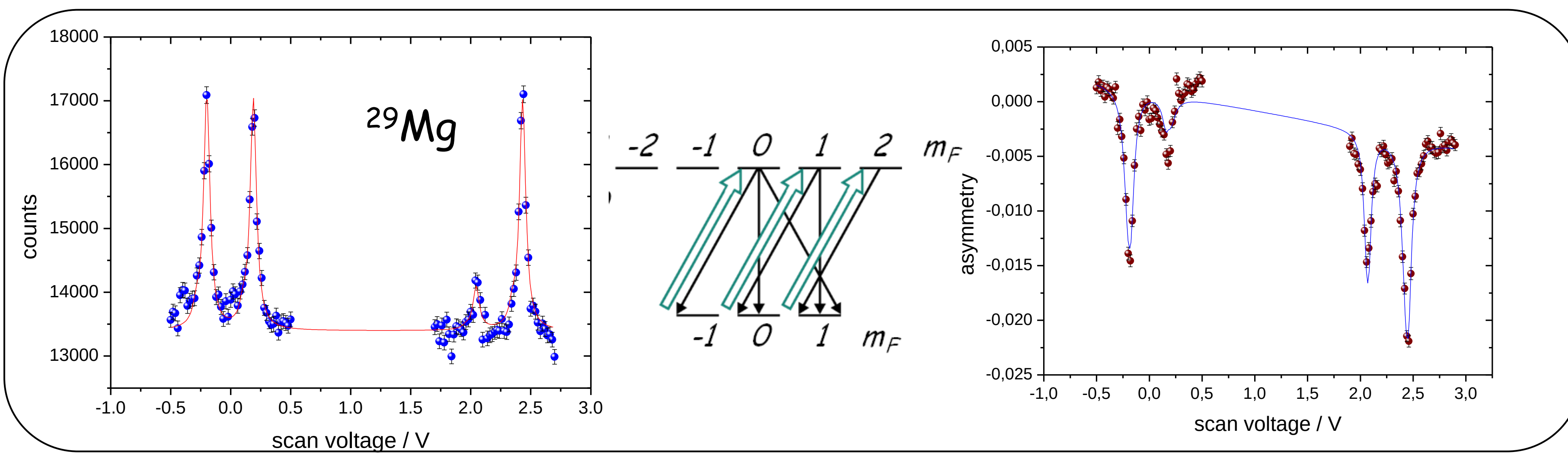
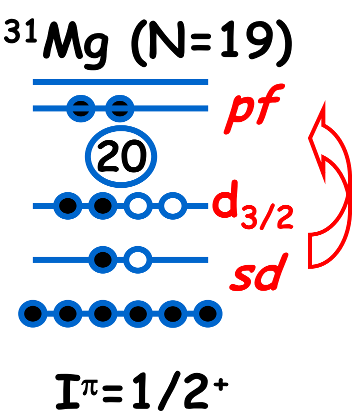


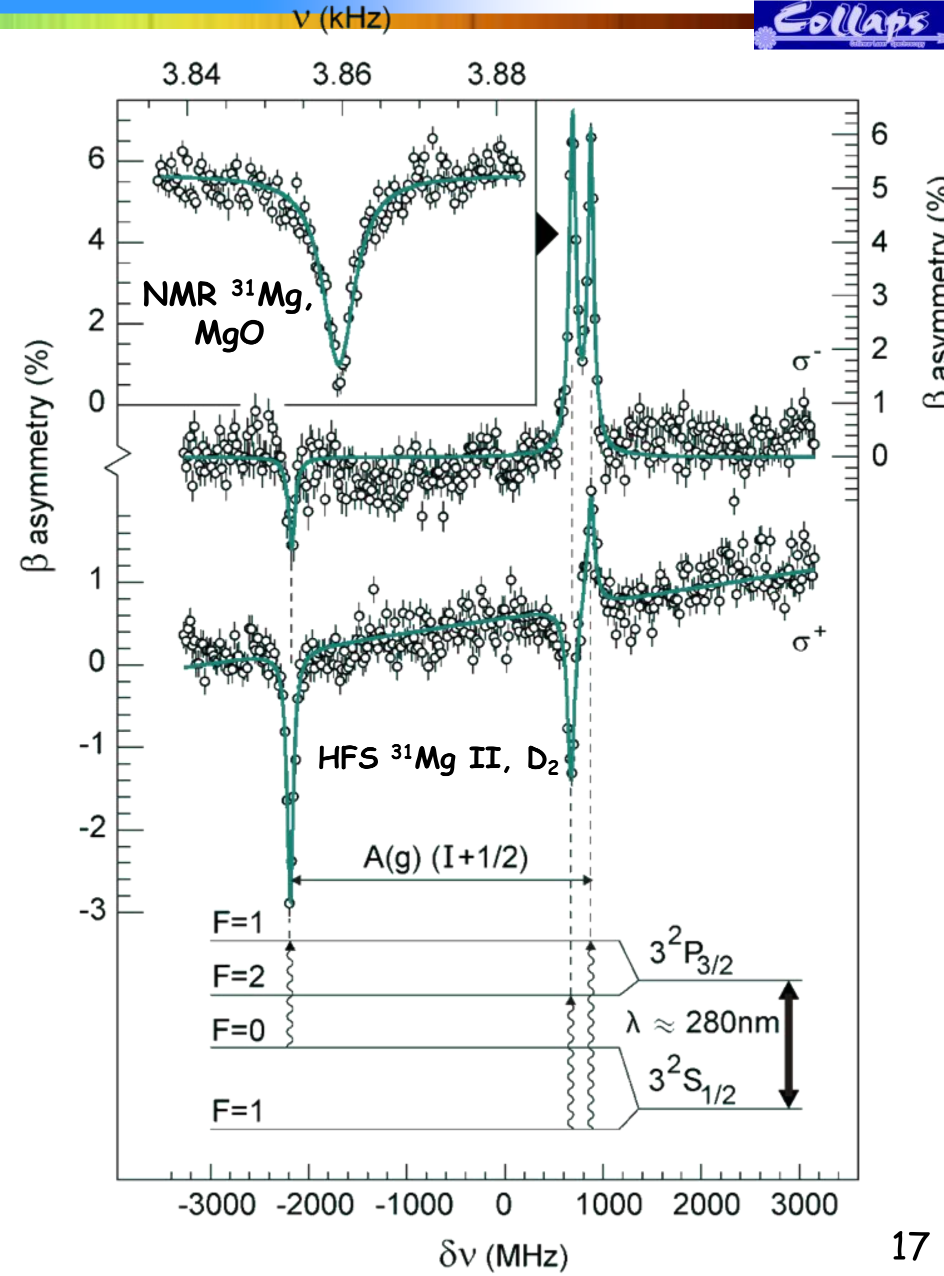
acceleration → deflection → Doppler tuning → optical detection



β-Nuclear Magnetic Resonance in Mg

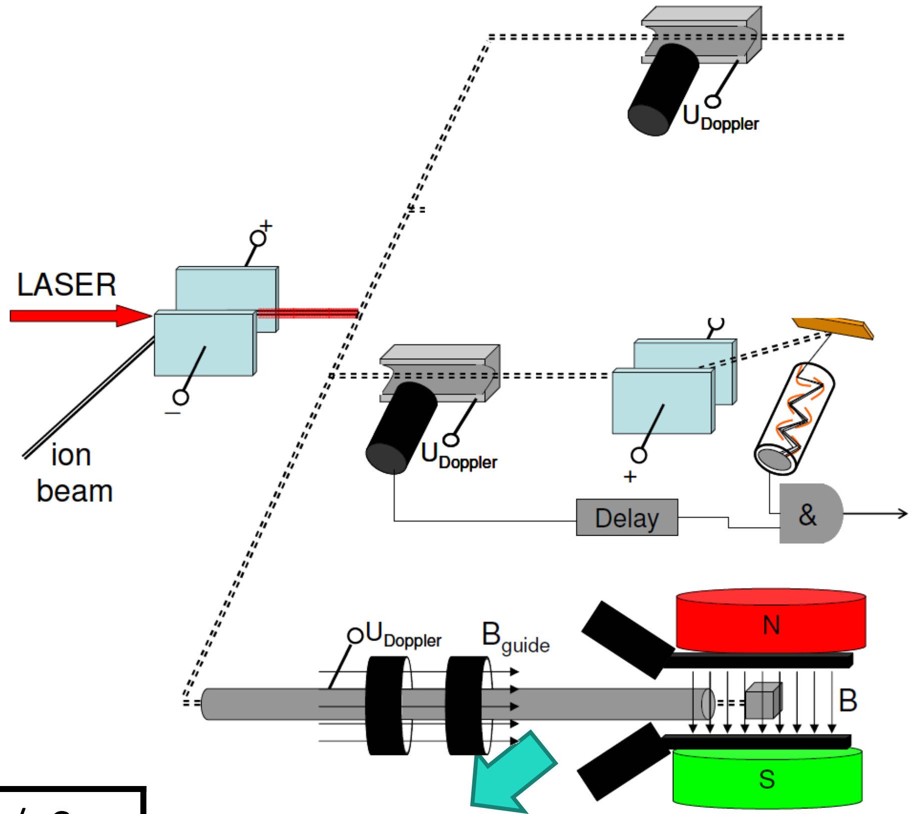
REAL ground state configurations:

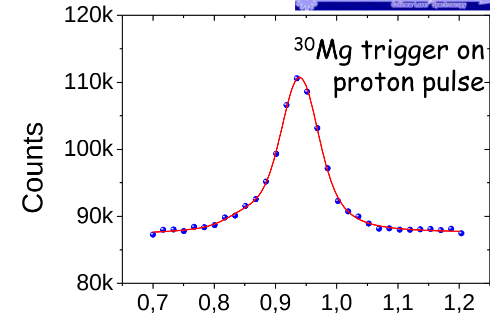


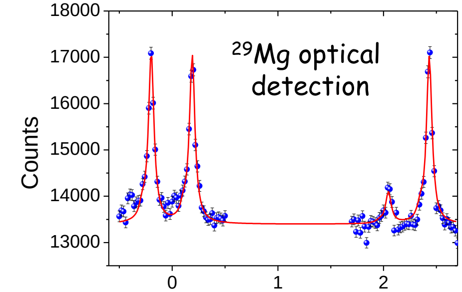


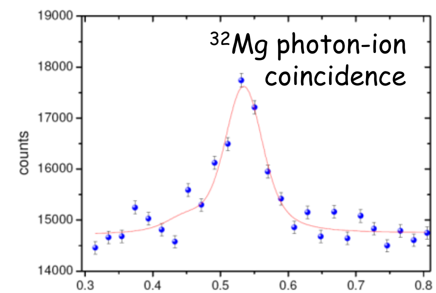
G. Neyens *et al.*, Phys. Rev. Lett. **94**, 022501 (2005)
D. Yordanov *et al.*, Phys. Rev. Lett. **99**, 212501 (2007)
M. Kowalska *et al.*, Phys. Rev. C **77**, 034307 (2008).

Isotope Shift Determination in the Mg Chain: Techniques









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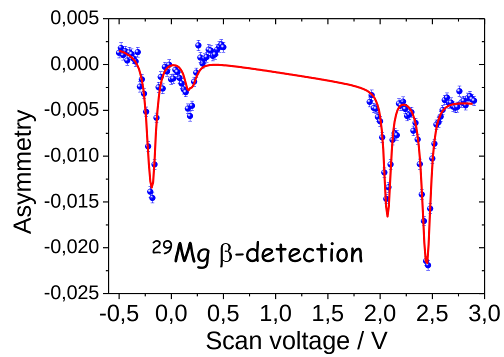
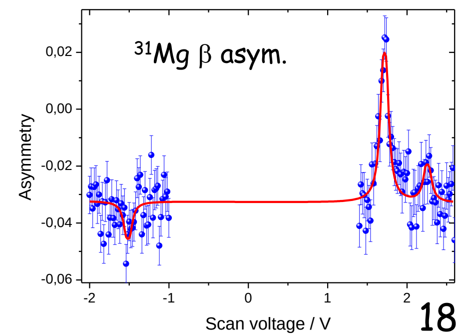
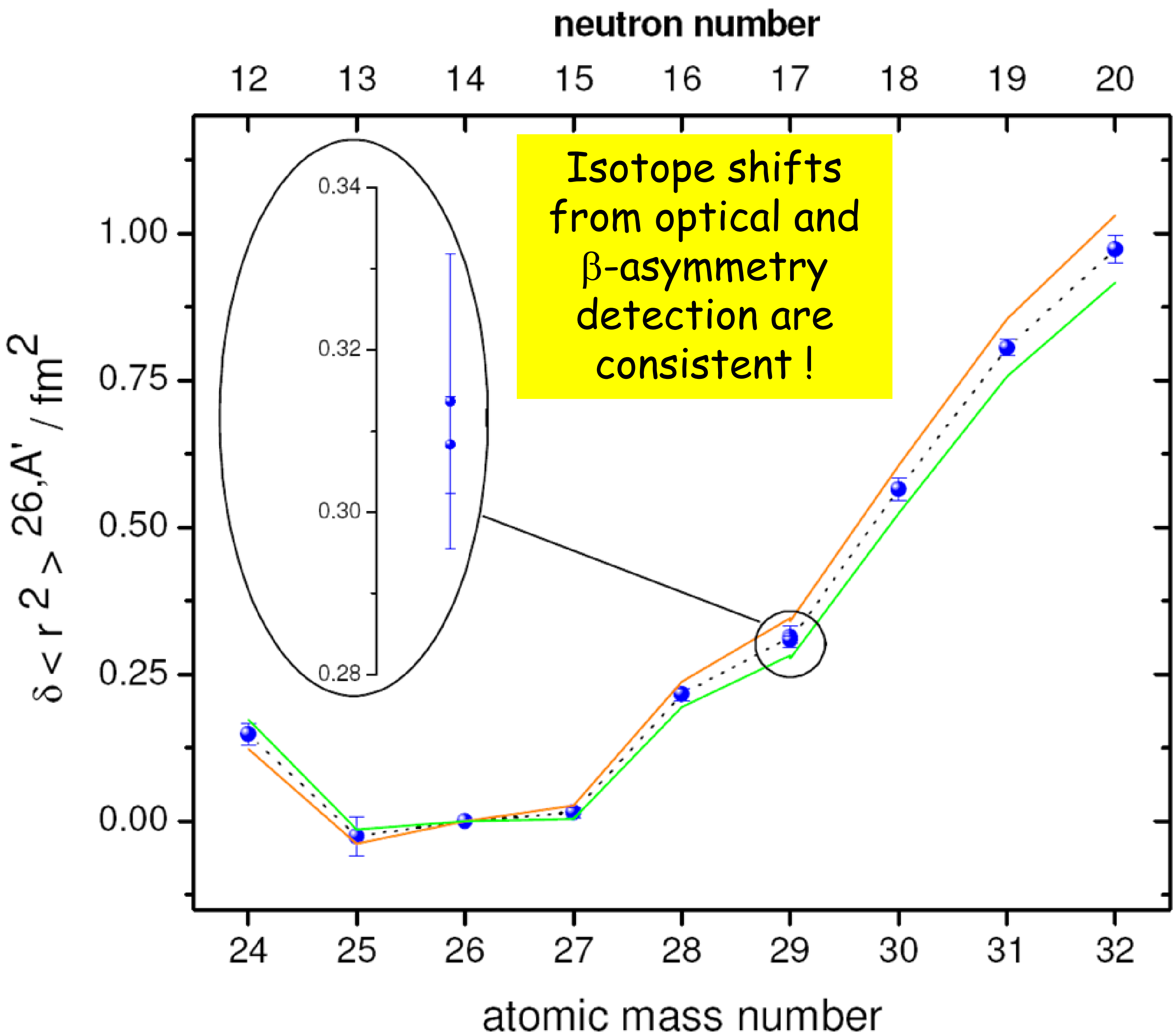




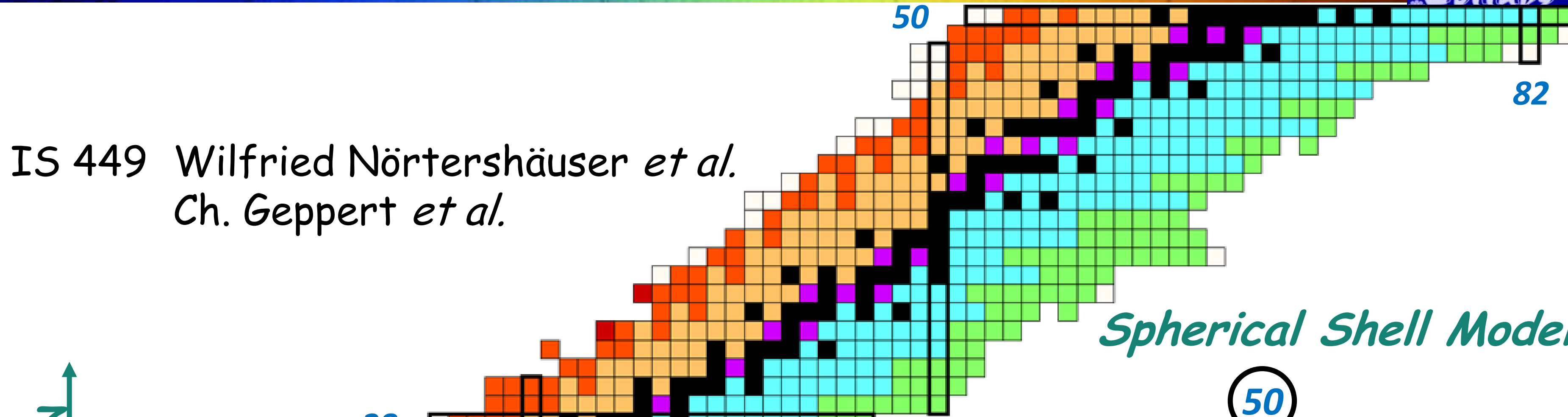
Change in Charge Radii from ^{24}Mg to ^{32}Mg

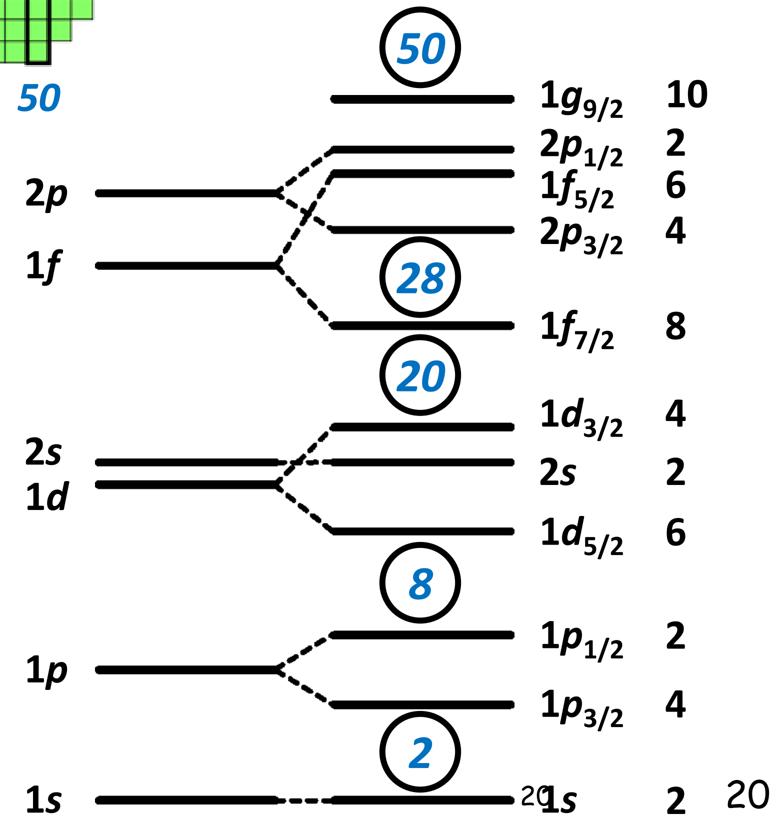


J. Krämer, PhD Thesis, University Mainz (2010)

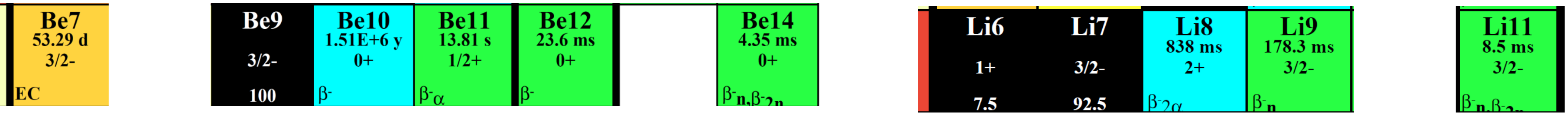
Light Elements: The Realm of Halo Nuclei

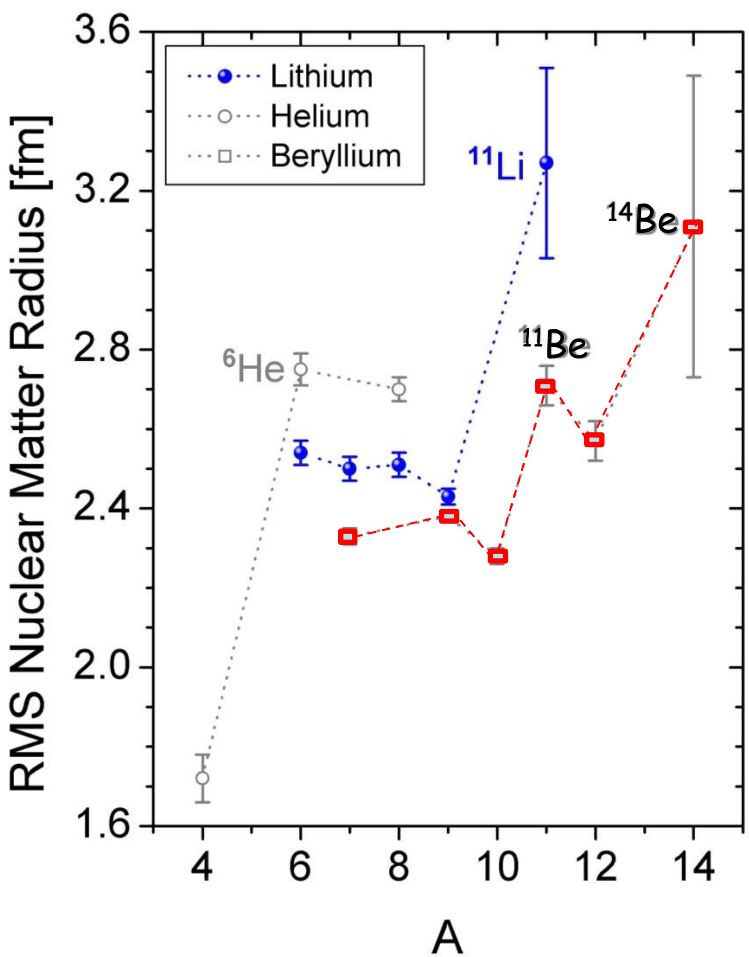
IS 449 Wilfried Nörtershäuser *et al.*
Ch. Geppert *et al.*

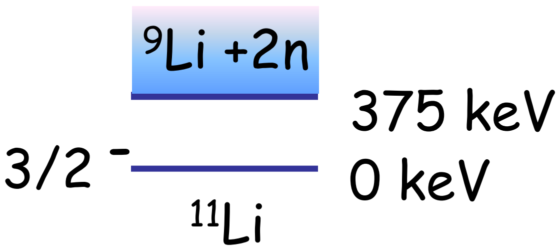




Halo Nuclei

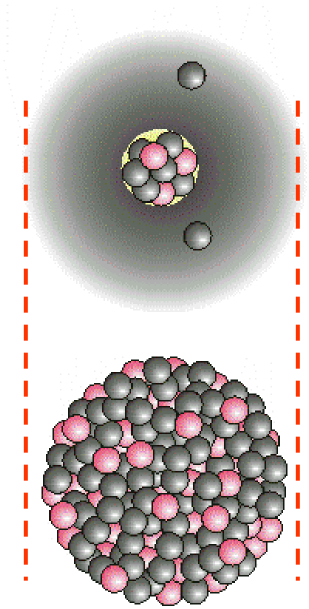






Neutron Halo

Stable nuclei



^{11}Li

^{208}Pb

Charge Radii Determination of Lightest Elements

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

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

$F = 16.912\ \mathrm{MHz/fm}^2$

EXPERIMENT

THEORY

Experiment AND Theory:
Accuracy of ~ 100 kHz in 40 GHz
($\Delta\nu/\delta\nu_{IS} = 3 \times 10^{-6}$)
Experimental:
Low Yields → High sensitivity
Short Lifetimes → Fast

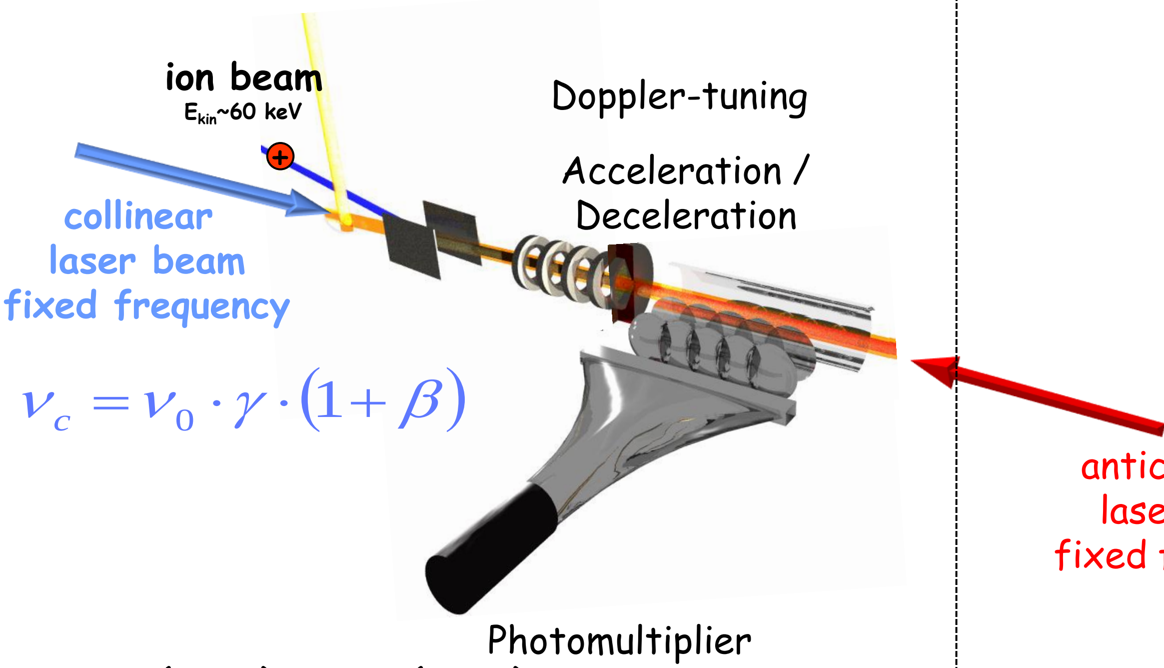
Isotope	$\delta\nu_{MS}$, MHz [Puch08]	$\delta\nu_{MS}$, MHz [Yan 08]
^{7}Be	-49 225.736(35)(9)	-49 225.780 (39)
^{10}Be	17 310.437(13)(11)	17 310.442 (13)
^{11}Be	31 560.302 (31)(12)	31 560.087 (24)

[Puch08] M. Puchalski and K. Pachucki, PRA (2008), in print
[Yan08] Z.-C. Yan, W.Nörtershäuser, G.W.F. Drake, PRL **100**, 243002 (2008) + newest mass values

Limitations of CLS for Light Elements

The Solution

„CONVENTIONAL SETUP“



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

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

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

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

Impossible for Light Elements (Z<10) !!

NEW APPROACH

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

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

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

Completely independent of U !

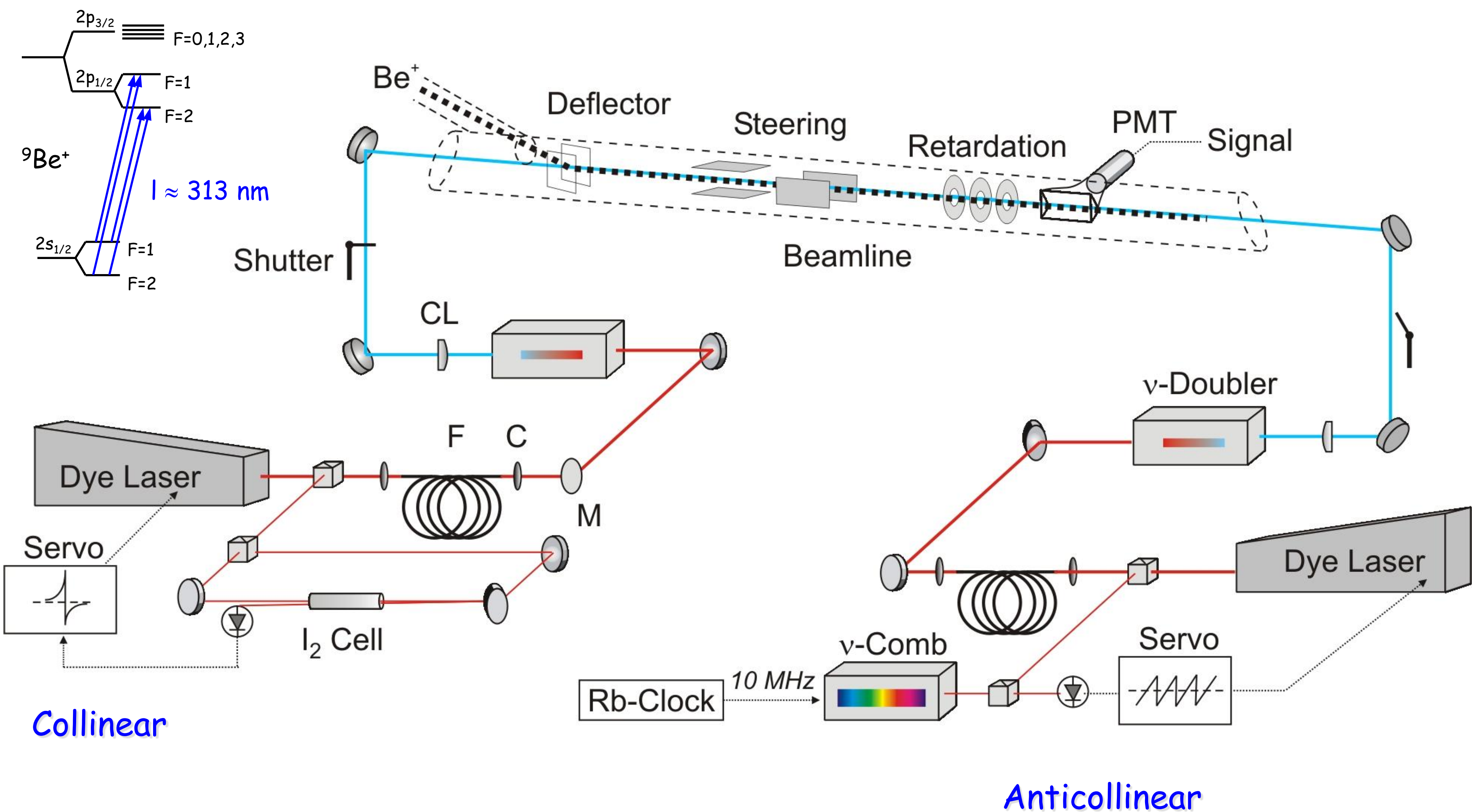
Requirements:

Measure absolute frequencies

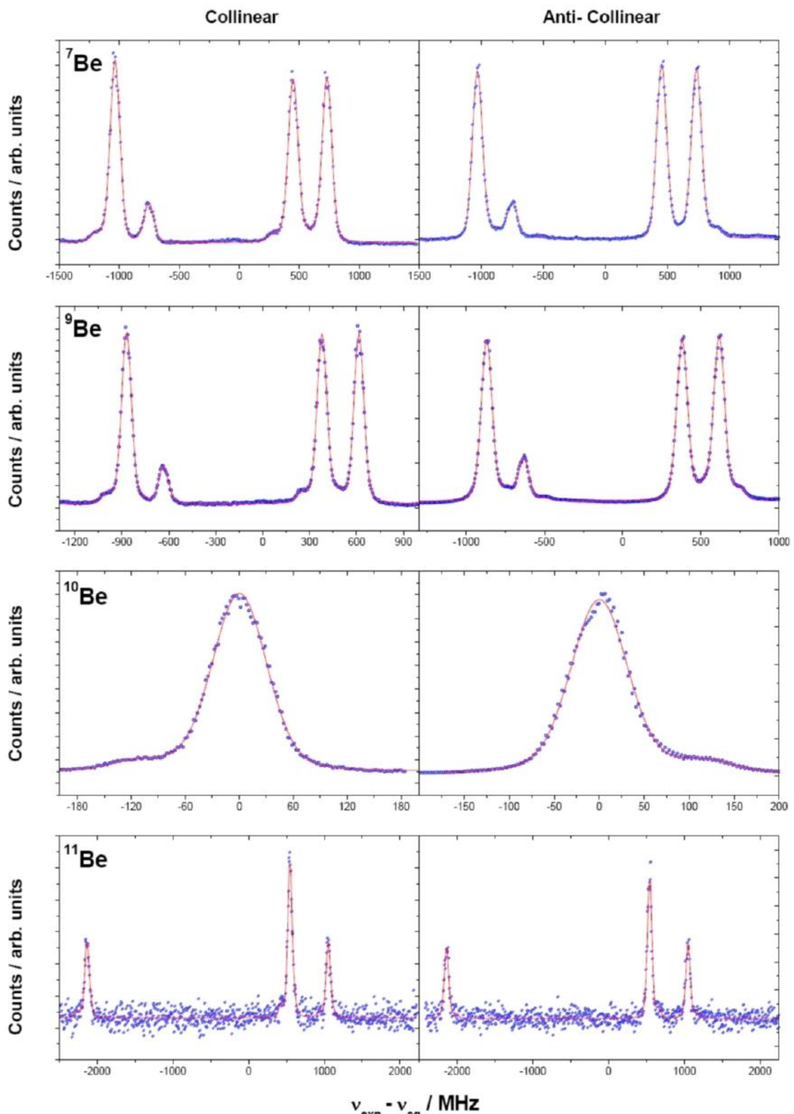
Accuracy: $\Delta\nu/\nu < 10^{-9}$

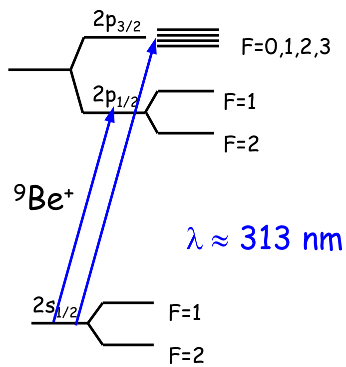
Dedicated Laser System for absolute Frequency Measurements

Experimental Setup

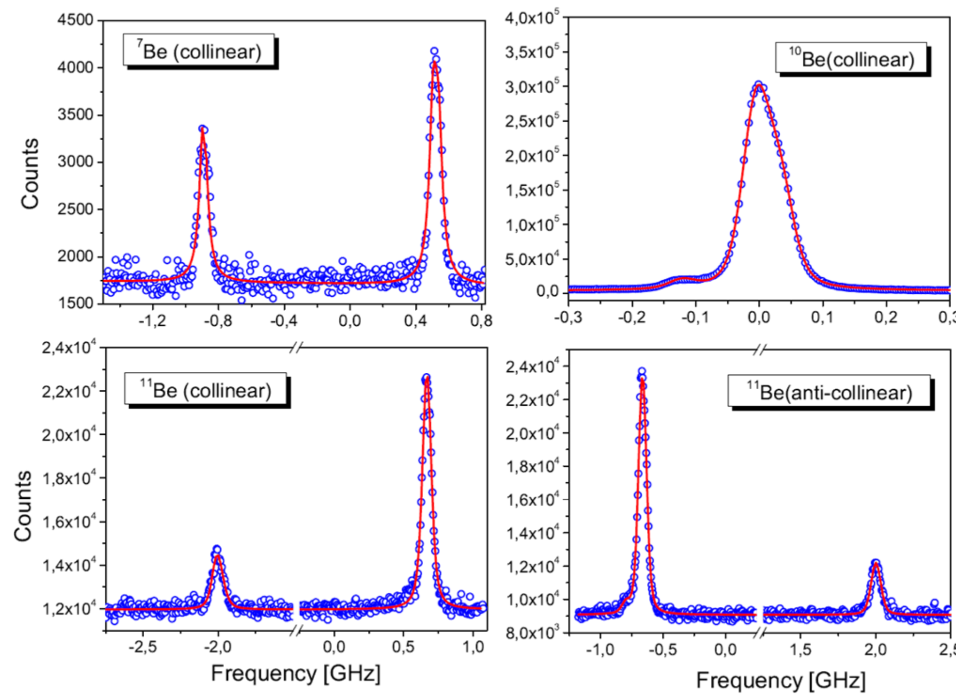


Results: Absolute Transition Frequencies



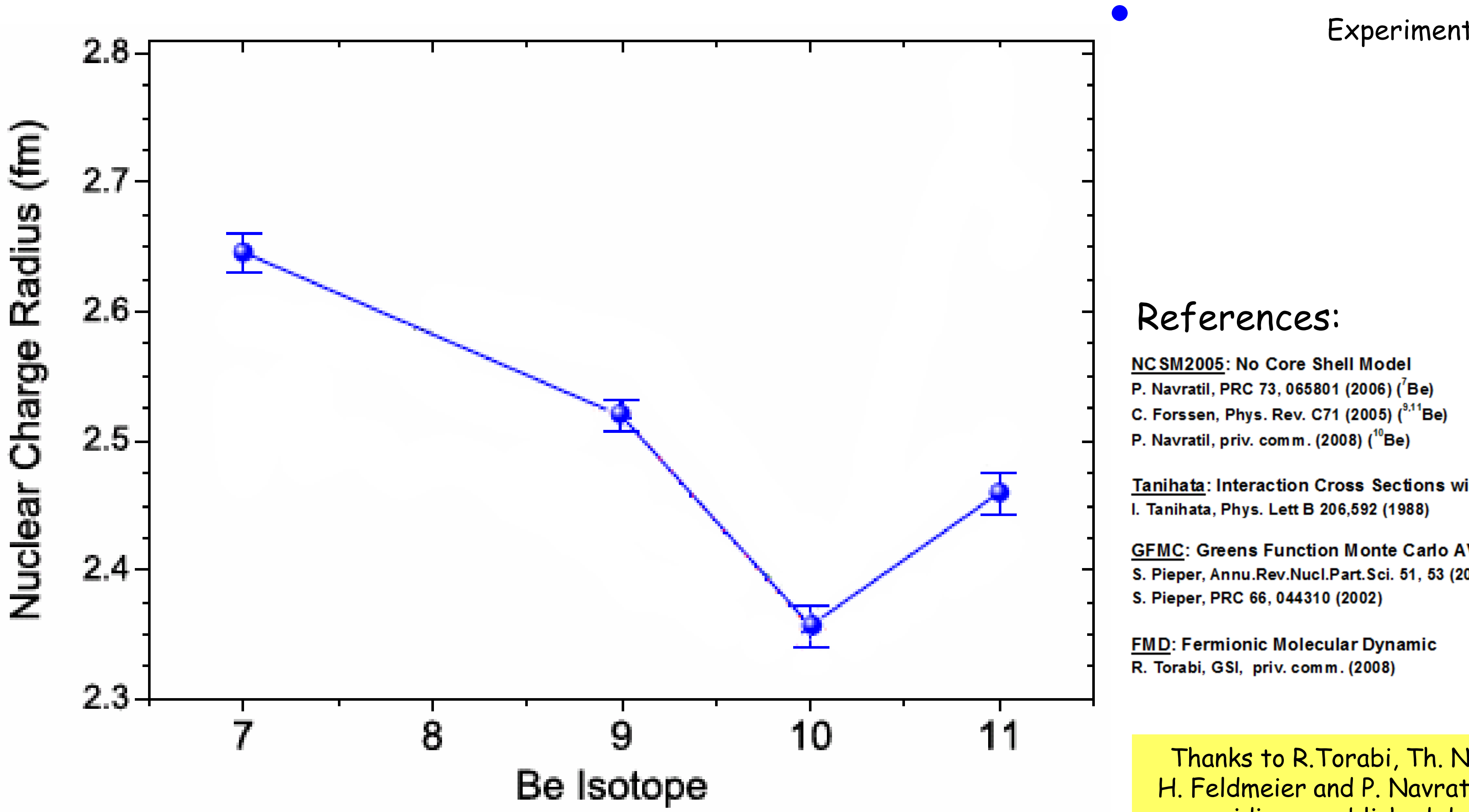


isotope	absolute frequency ν_0	$\Delta\nu_0$
Be	*GHz*	*MHz*
7	957150,31638	1,68
9	957199,55326	1,54
10	957216,87706	2,05
11	957231,11826	1,41



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).



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
I. Tanihata, Phys. Lett B 206,592 (1988)

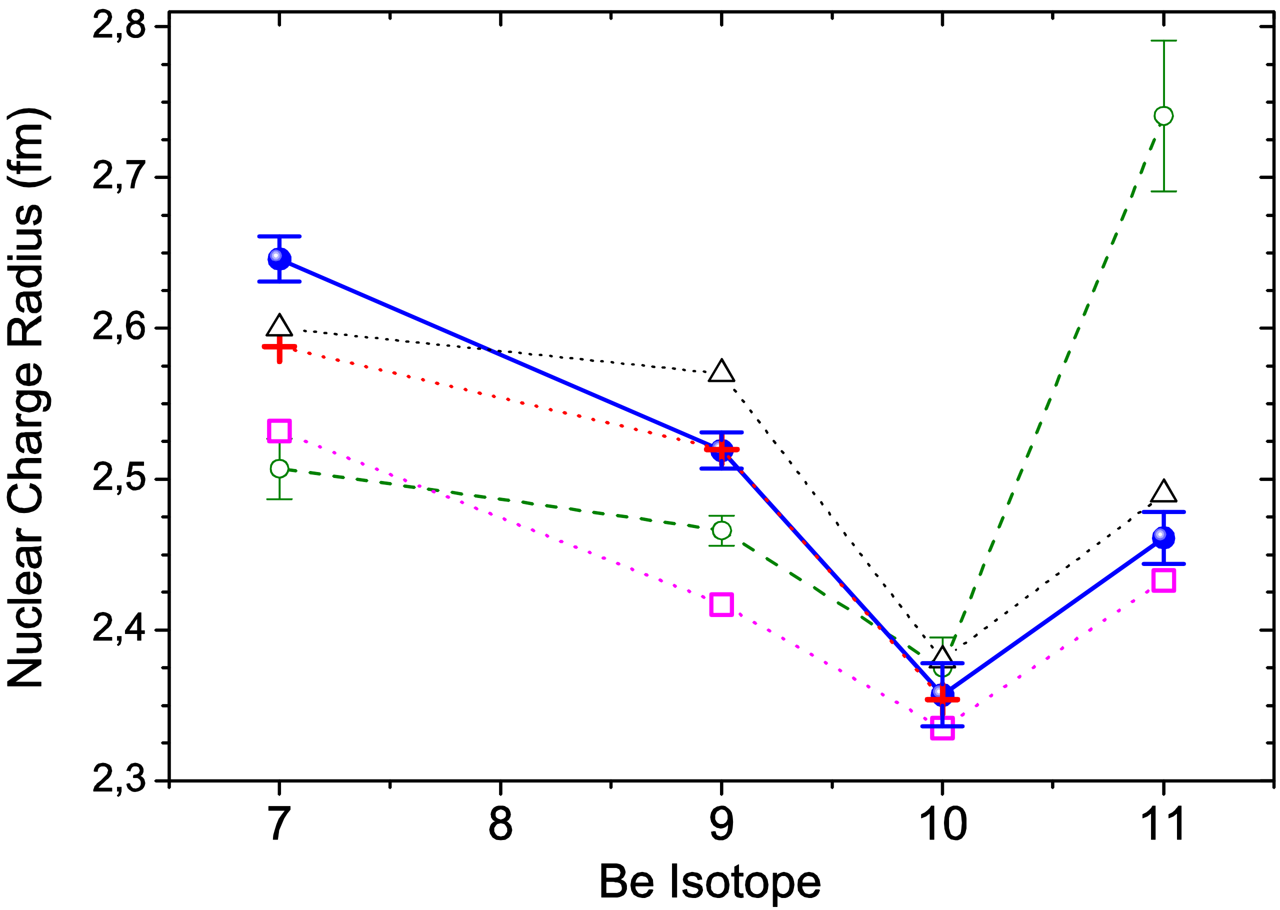
GFMC: Greens Function Monte Carlo AV18/IL2
S. Pieper, Annu.Rev.Nucl.Part.Sci. 51, 53 (2001)
S. Pieper, PRC 66, 044310 (2002)

FMD: Fermionic Molecular Dynamic
R. Torabi, GSI, priv. comm. (2008)

Thanks to R.Torabi, Th. Neff, H. Feldmeier and P. Navratil for providing unpublished data !

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
- ○ Interaction cross section (Tanihata)
- + Greens-Funct. Monte-Carlo Calcul.
- Δ Fermonic Molecular Dynamics
- □ No-Core Shell Model

References:

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C. Forssen, Phys. Rev. C71 (2005) (^{9,11}Be)
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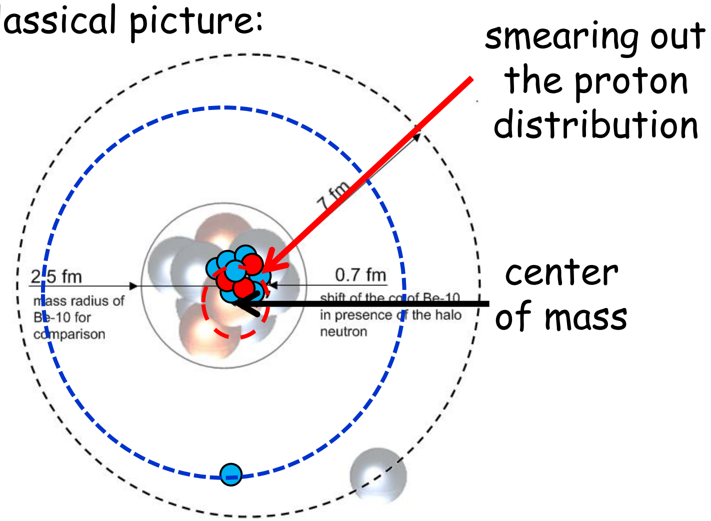
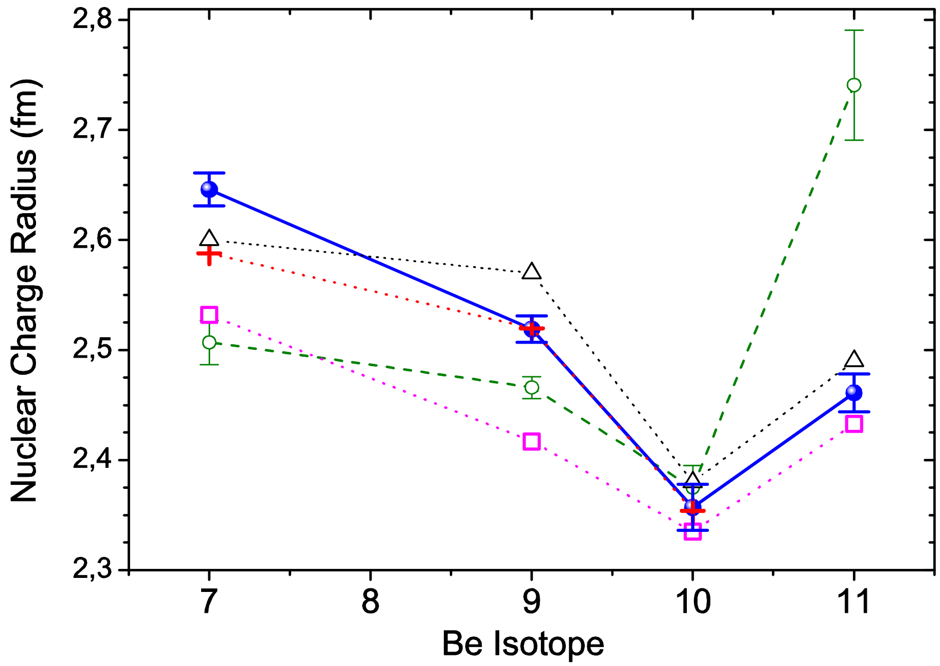
Three-Body Model of ^{11}Be

Pure center-of-mass motion

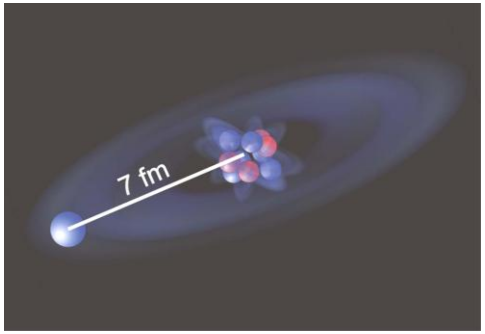
classical picture:



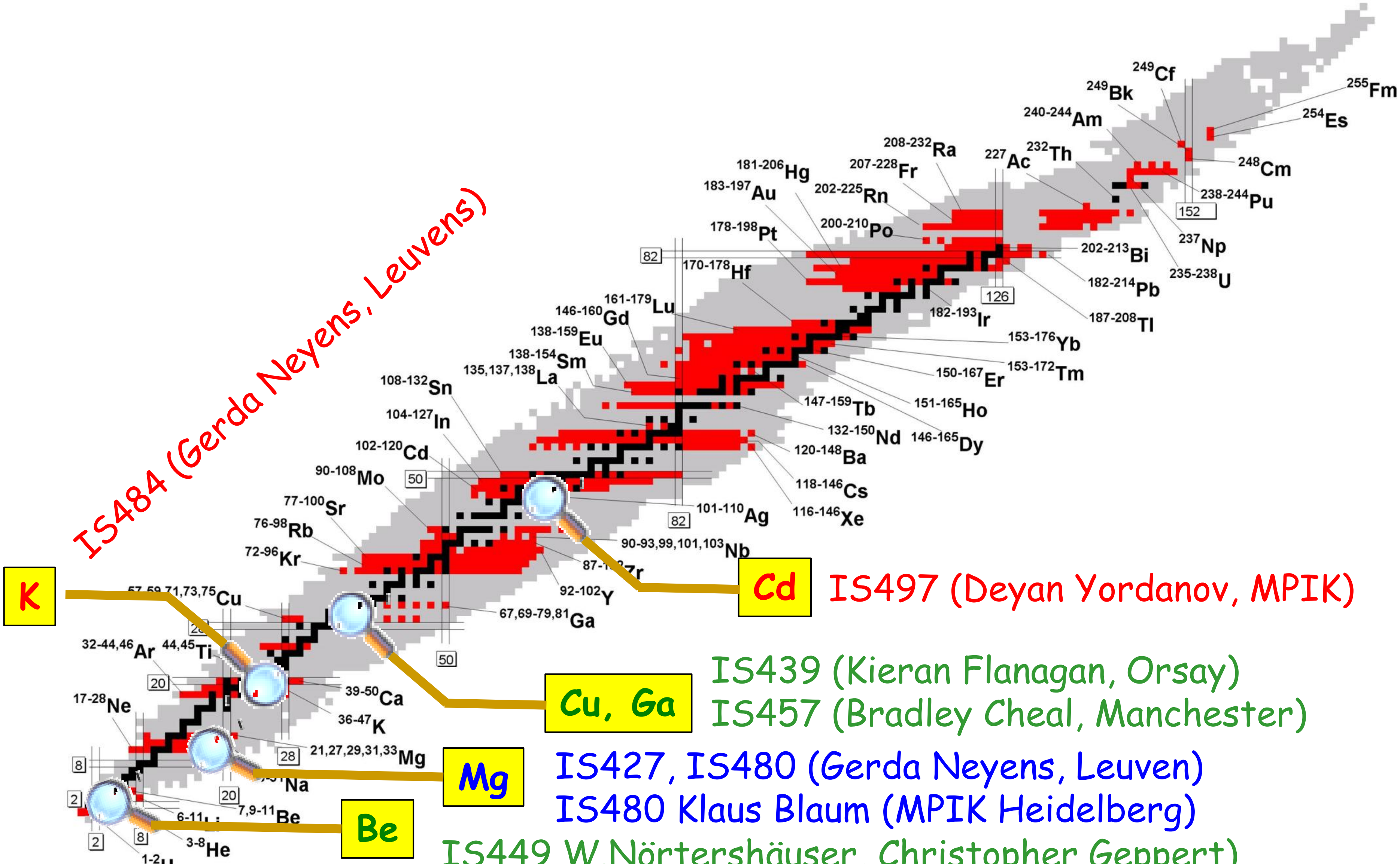


$$r_c^2\left({}^{11}Be\right) = R^2_{centermass} + r_c^2\left({}^{10}Be\right)$$

$$r_{halo-Neutron} = R_{centermass} \cdot \frac{m({}^{10}Be)}{m(Neutron)}$$



Proposals at COLLAPS:
Data Taking, in Preparation, Recently Completed



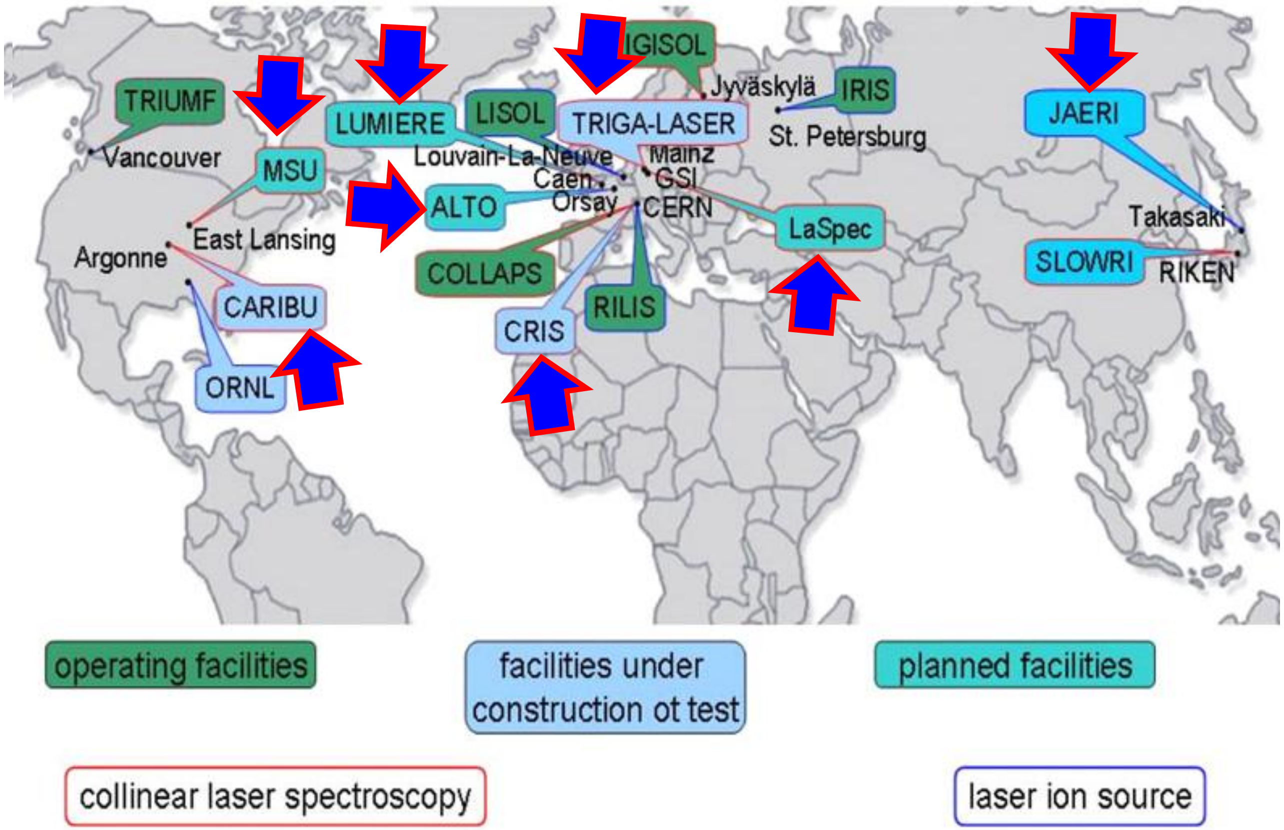
IS497 (Deyan Yordanov, MPIK)

IS439 (Kieran Flanagan, Orsay)
IS457 (Bradley Cheal, Manchester)

IS427, IS480 (Gerda Neyens, Leuven)
IS480 Klaus Blaum (MPIK Heidelberg)

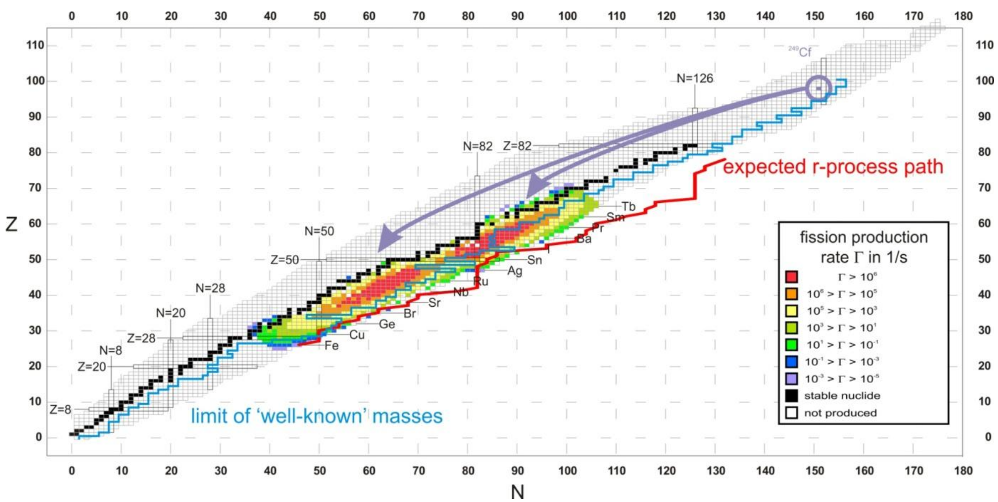
IS449 W.Nörtershäuser, Christopher Geppert)

Productive and Emerging CLS Setups

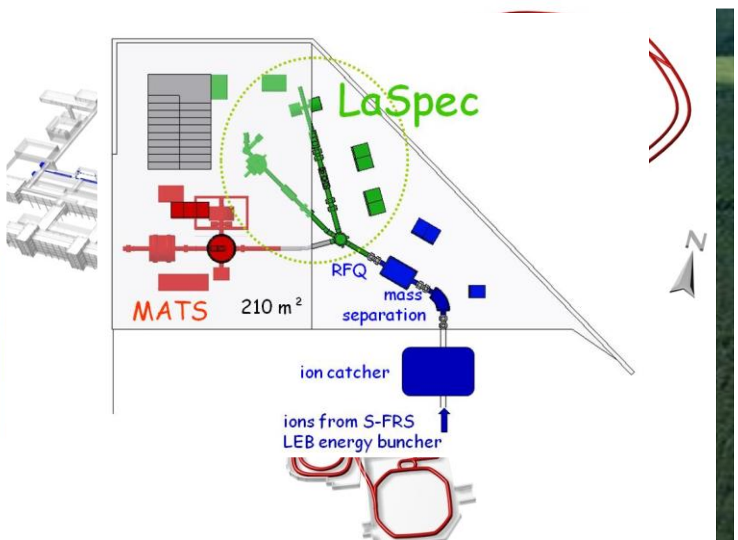


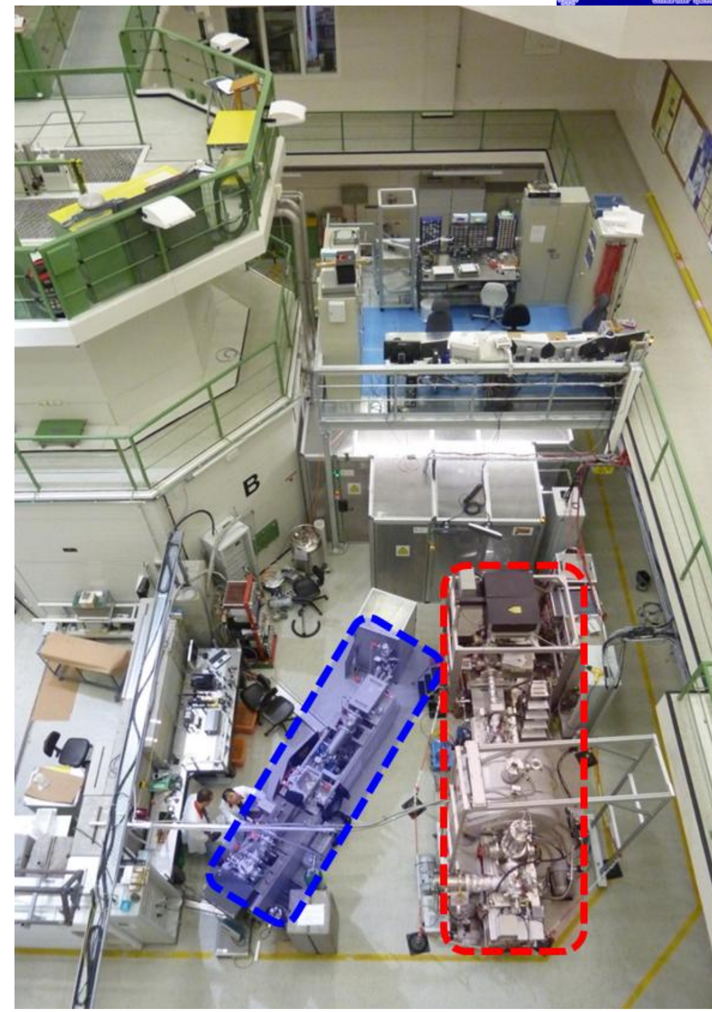
COLLAPS (ISOLDE, HI-ISOLDE), JYFL (Manchester / Jyväskylä):
CRIS (ISOLDE) : high sensitivity using Resonance Ionization Spectroscopy;
BECOLA (NSCL-MSU) : light in-flight fragments stopped in a gas cell and re-accelerated;
CARIBU (ANL): spontaneous fission products of ^{252}Cf, gas-cell, re-accelerated;
TRIUMF: ISOL, lanthanides, electromagnetic moments of ^{11}Li;
ALTO: photoinduced fission;
LUMIERE (DESIR, SPIRAL2): spallation, fragmentation, fission;
TRIGA-LASER (TRIGA-SPEC) → LASPEC @ FAIR Actinides, n-induced fission of ^{249}Cf → „Menu" of FRS

TRIGA-SPEC (LASPEC + MATS)



J. Ketelaer, Nucl. Instr. Meth. A 594 (2008) 162





LASPEC / MATS / SHIPTRAP
(Prototyping & Development)

W. Nörtershäuser, P. Campbell and the LaSpec collaboration, Hyperfine Interactions **171**, 149 (2006)
Technical Design Report: D. Rodriguez *et al.*, Eur. Phys. J. Special Topics **183**, 1-123 (2010)

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