Max Planck Institute for Nuclear Physics

ECT Trento "The Lead Radius …"*

"Precision measurements of nuclear ground state properties for nuclear structure studies "

Klaus Blaum

04.08.2009

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Outline

- Introduction, history and methods
- Principle of laser spectroscopy and mass spectrometry
- Setup and measurement procedure
- Precision measurements of nuclear ground state properties

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Nuclear ground state properties

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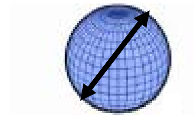
ISOTOPE SHIFT

Finite Size Effect

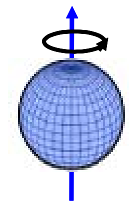
$\Rightarrow$ Change of Charge Radius



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

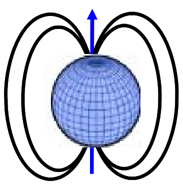
HYPERFINE STRUCTURE

1. Hyperfine Interaction
   $\Rightarrow$ nuclear spin



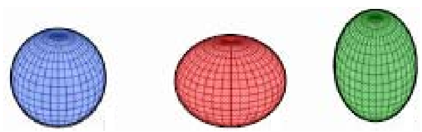
$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$

2. Magnetic Dipole HFS
   $\Rightarrow$ nuclear magnetic moment



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

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



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

MASS

$\Rightarrow$ Nuclear Binding Energy

$E_{\mathrm{BIN}} = \Delta M\, c^2$

Model-independent determination of ground state properties.

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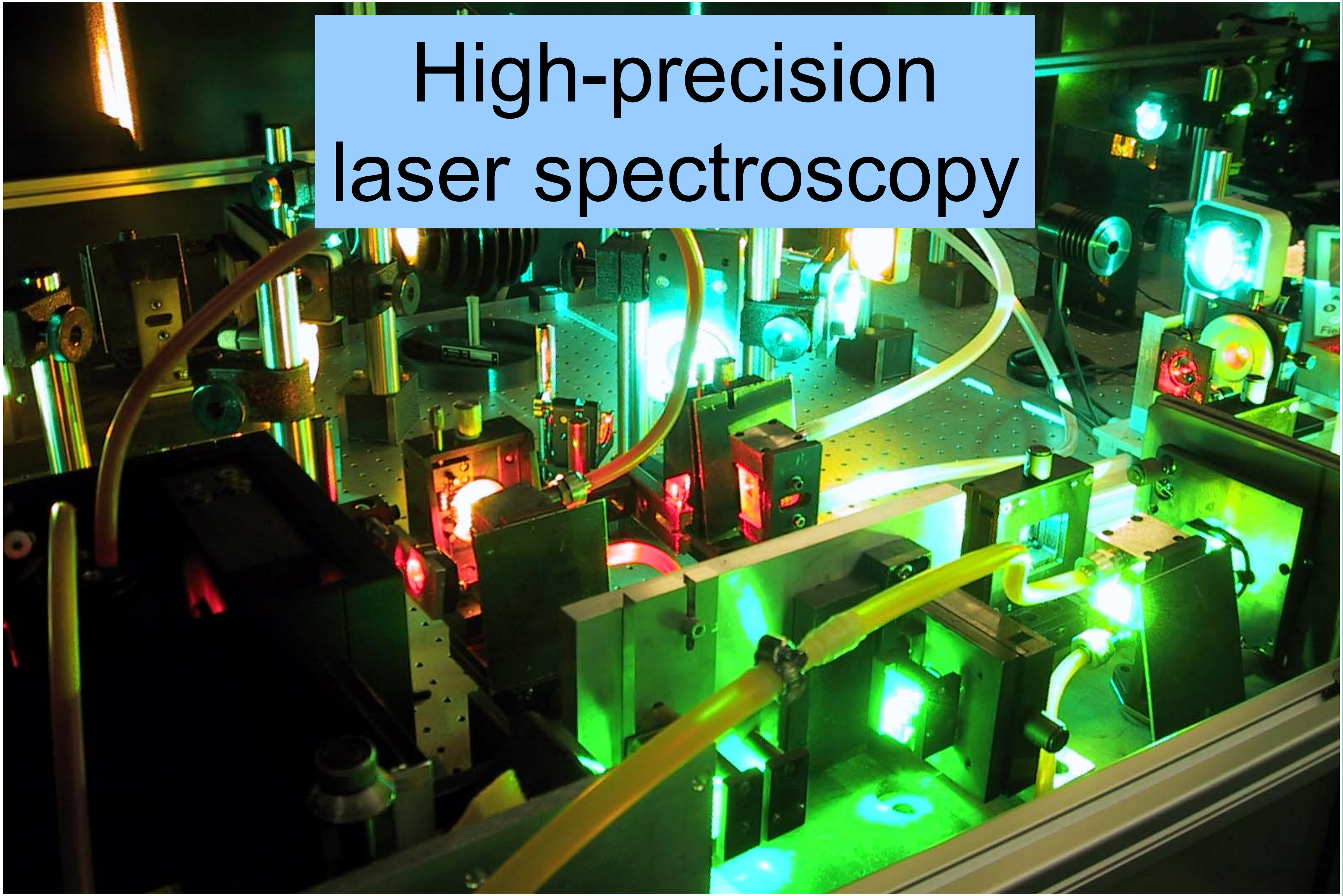
Part I

High-precision laser spectroscopy



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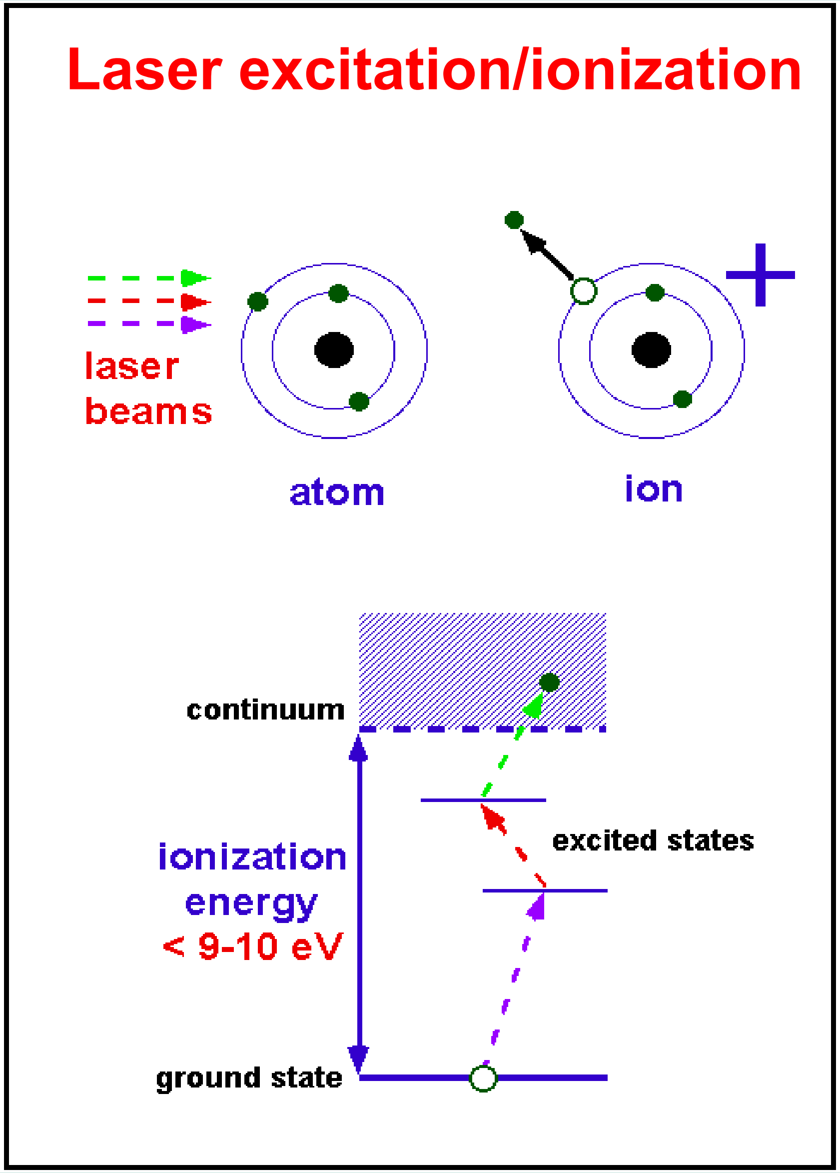
Principle of laser spectroscopy

Resonant step-wise excitation of one (or more) electrons in the electron shell of the atom.

The transition frequencies (wavelengths) are unique like a fingerprint for elements and isotopes.

Varying the laser frequency allows to probe different isotopes and elements.



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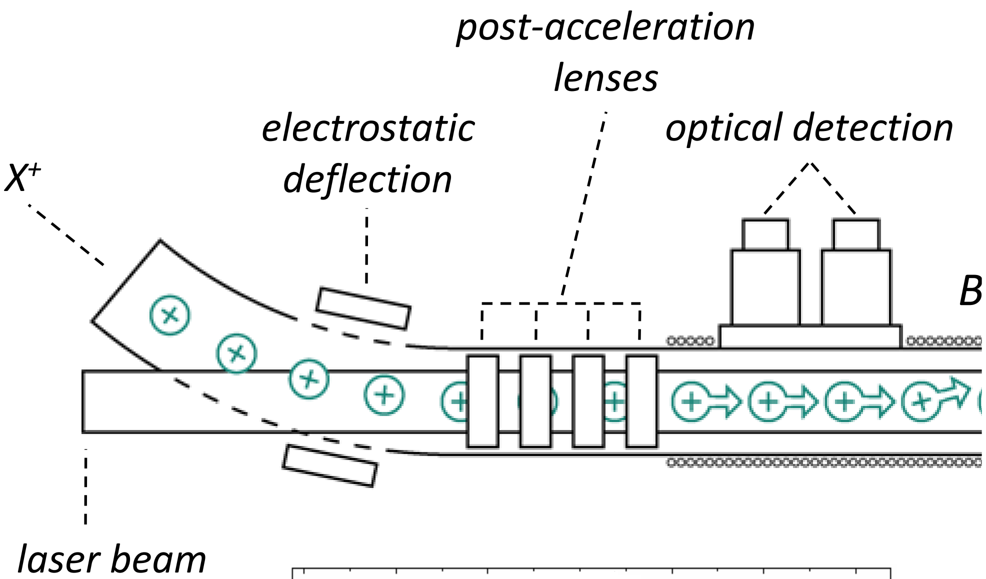
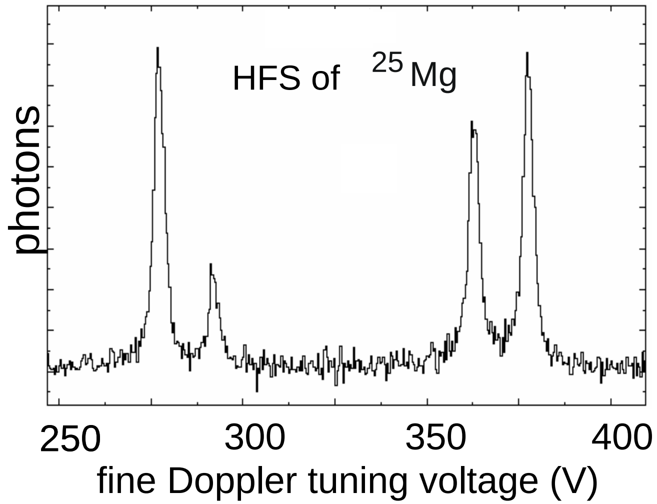
Collinear laser spectroscopy & β-NMR





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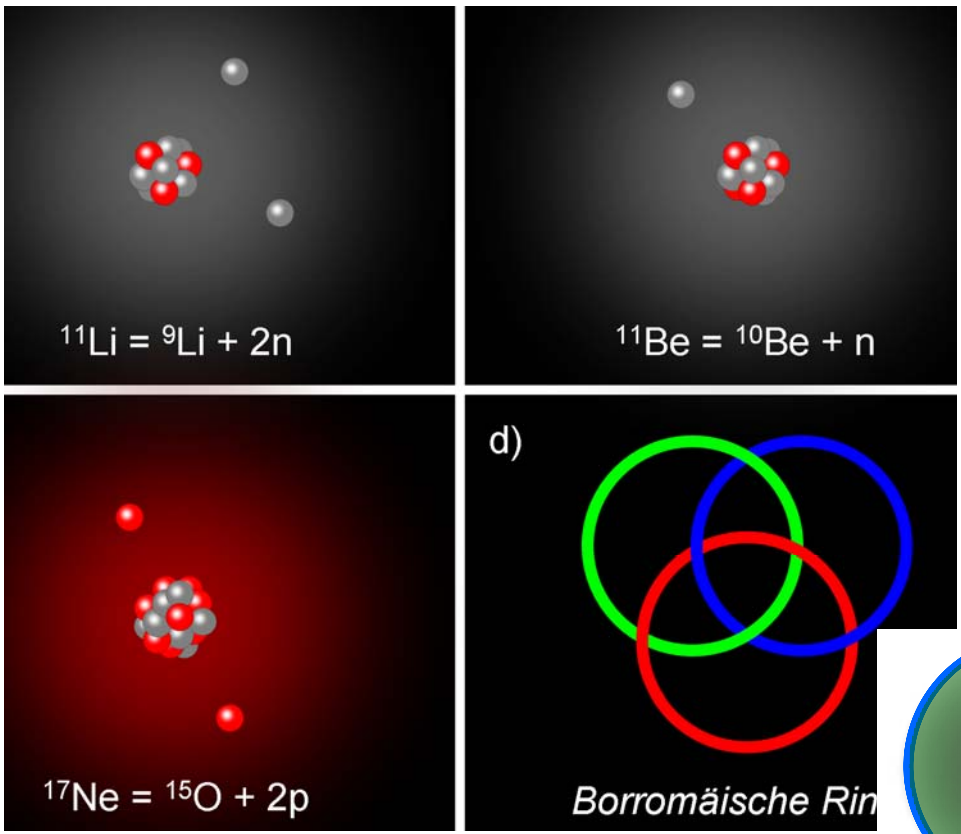
Investigation of nuclear halos

… via nuclear mass (binding energy) and charge radii measurements!

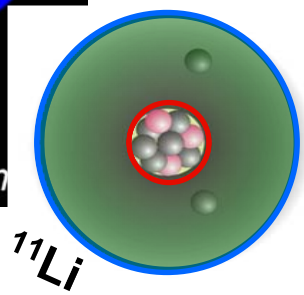


^{6,8}He:
P. Müller *et al.*, Phys. Rev. Lett. 99, 252501 (2007)

^{11}Li:
R. Neugart *et al.*, Phys. Rev. Lett. 101, 132502 (2008)

^{11}Be:
W. Nörtershäuser *et al.*, Phys. Rev. Lett. 102, 062503 (2009)

^{17}Ne:
W. Geithner *et al.*, Phys. Rev. Lett. 101, 252502 (2008)



isotope shift → R_{Charge}

Halo "=" R_{Matter} - R_{Charge}

nuclear reactions → R_{Matter}

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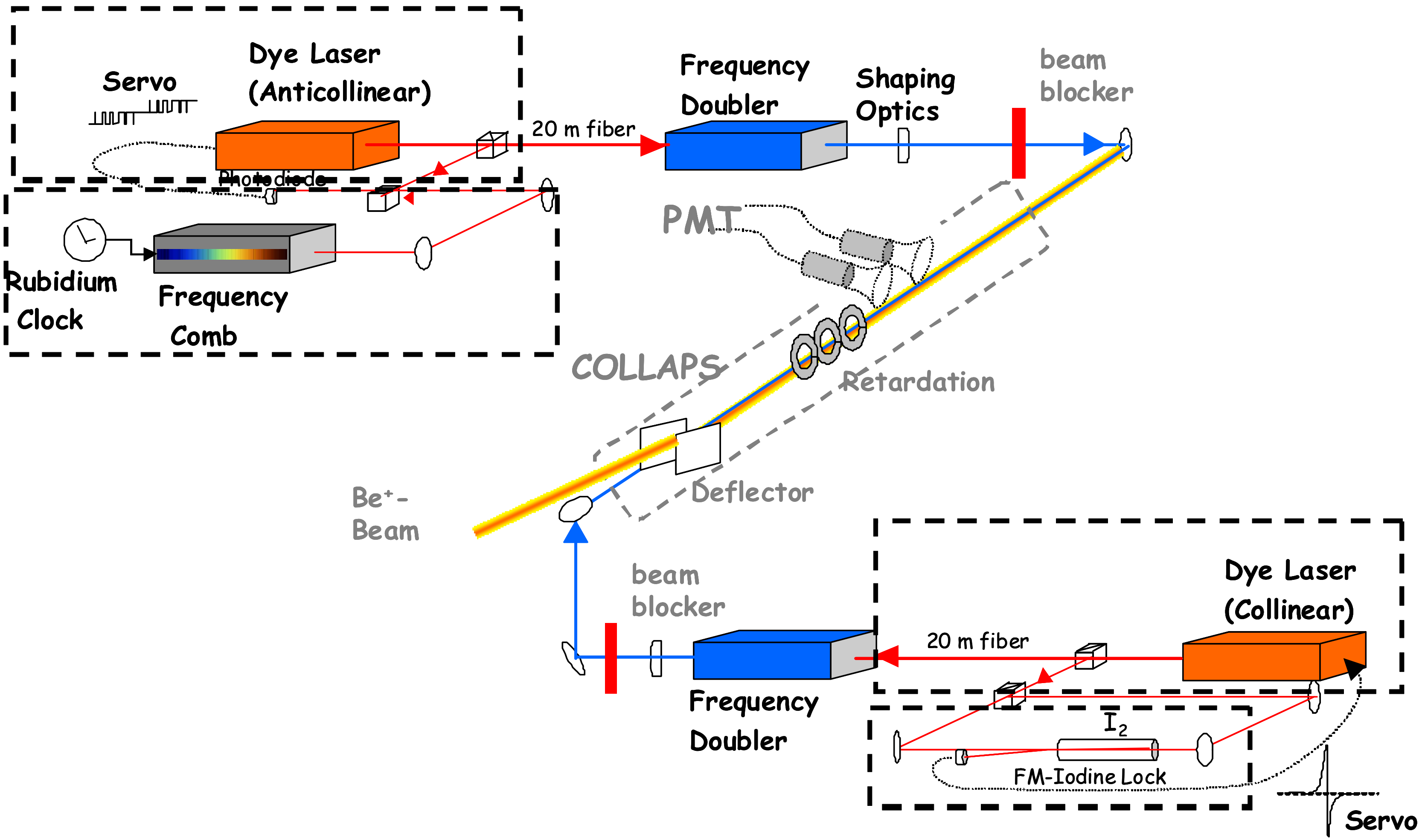
Be spectroscopy – laser system



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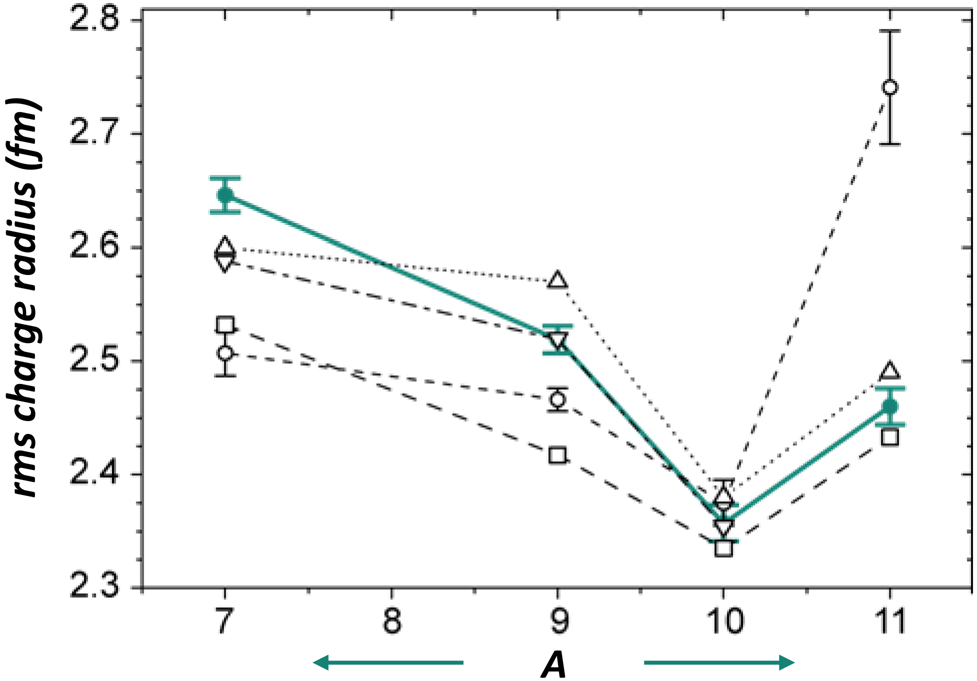
^{11}Be – nuclear charge radius



- *experiment*
- *No-Core Shell Model*
- *Fermionic Molecular Dynamics*
- *from interaction cross section exp.*
- *Greens-Function Monte-Carlo Calculations*

W. Nörtershäuser *et al*., Phys. Rev. Lett. 102, 062503 (2009)

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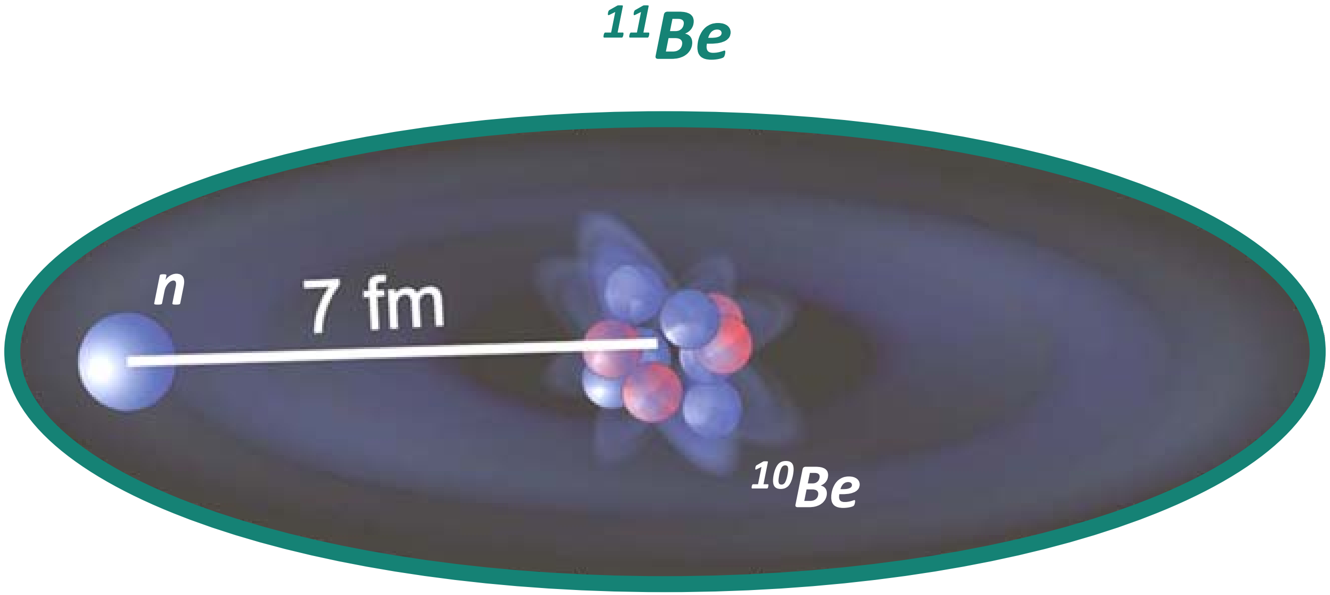
The simplified halo picture of ^{11}Be



W. Nörtershäuser *et al*., Phys. Rev. Lett. 102, 062503 (2009)

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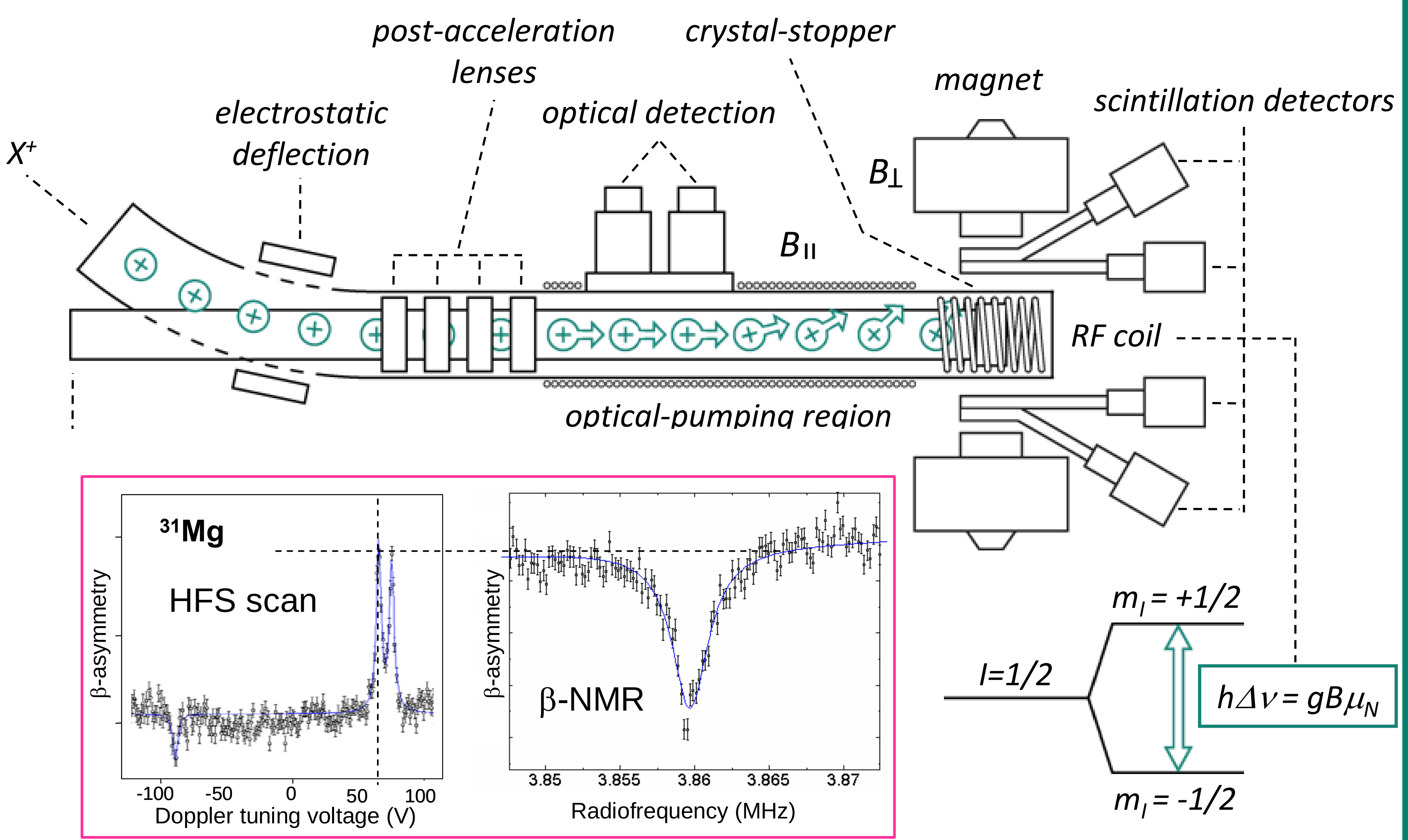
Collinear laser spectroscopy & β-NMR



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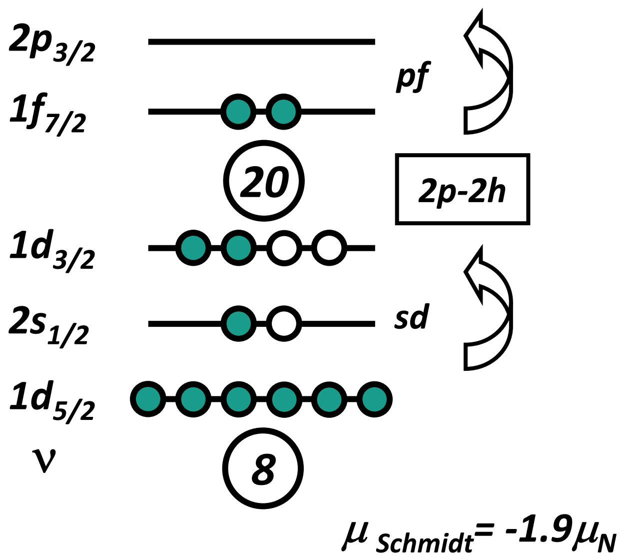
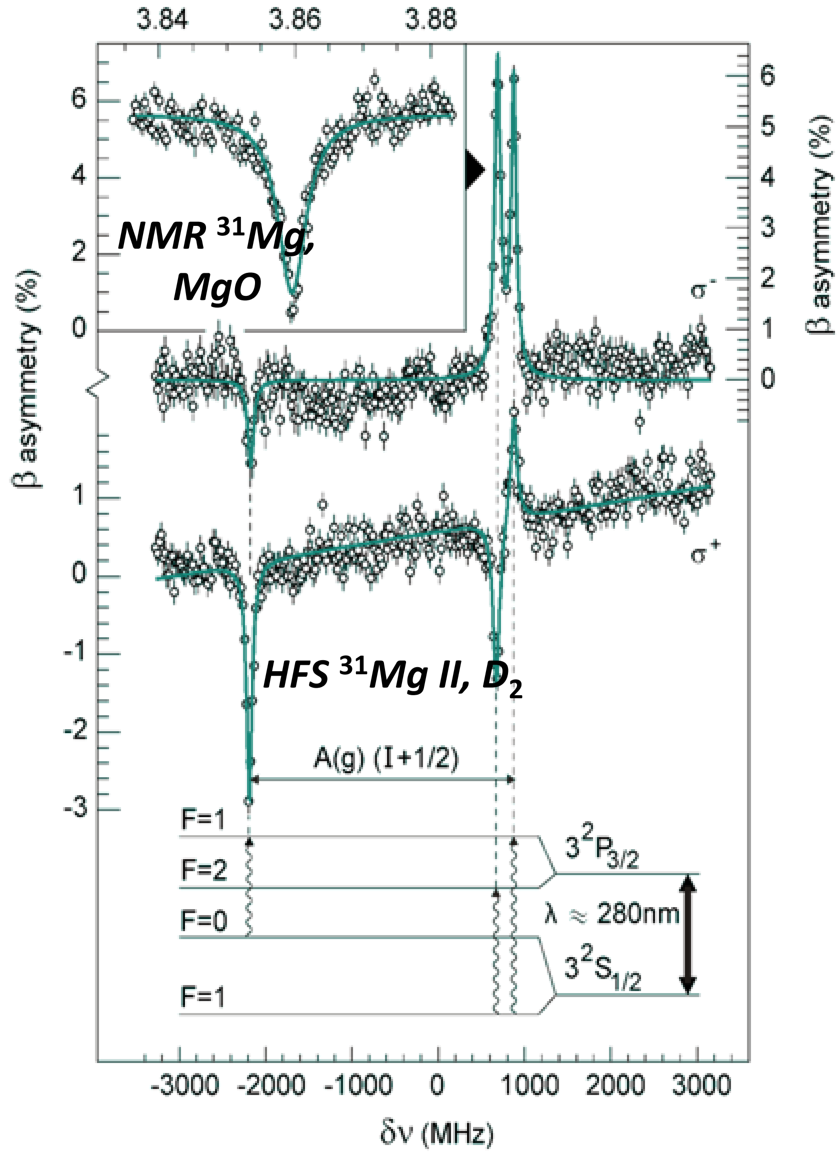
Spin and magnetic moment of ^{31}Mg

^{31}Mg (Z=12, N=19)





Ground-state properties of ^{31}Mg	
μ = -0.88355(15)μ_N	*I = 1/2*

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

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Part II

High-precision mass measurements

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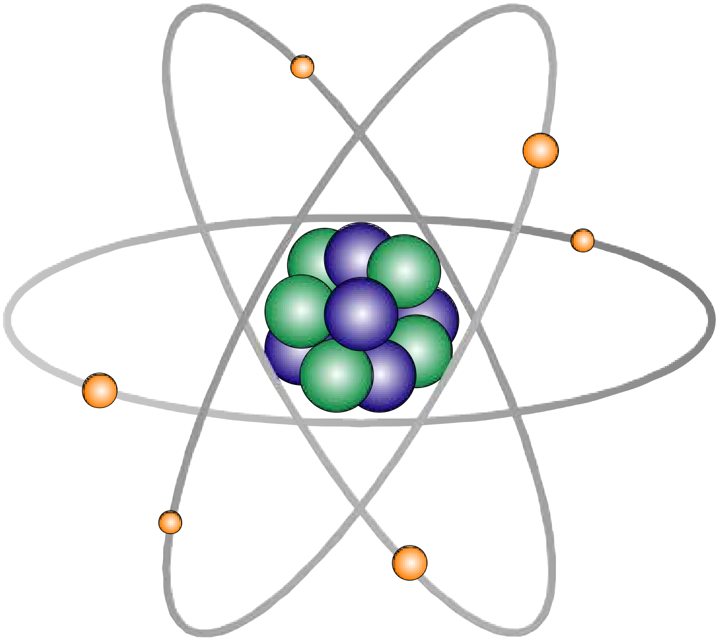
Applications of precision masses

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.



$= N \cdot$ $+ Z \cdot$ $+ Z \cdot$

– binding energy

$$M_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

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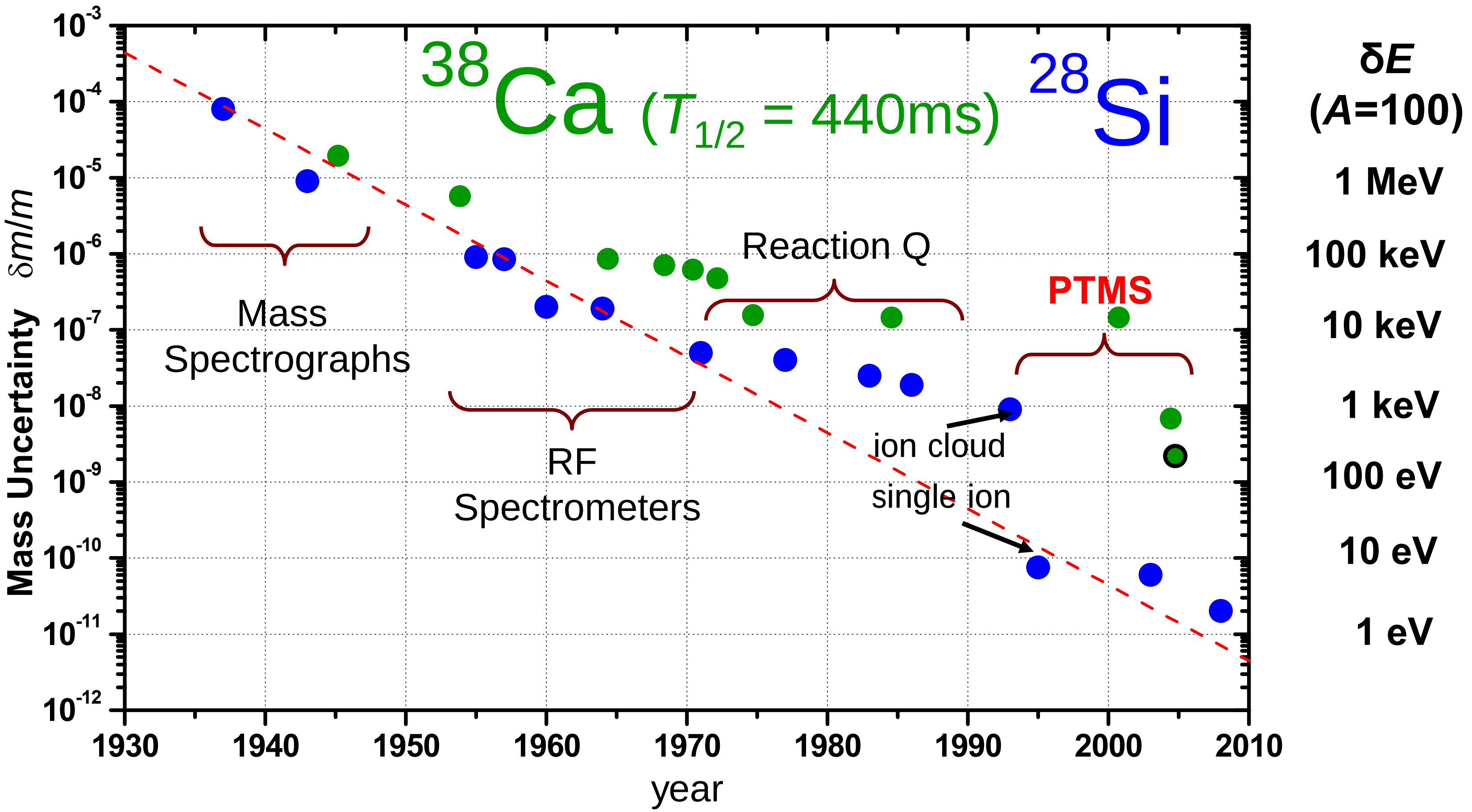
A brief history of mass spectrometry



SMILETRAP, MIT-TRAP (now at FSU), Seattle-TRAP, HD-TRAP

CPT, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP

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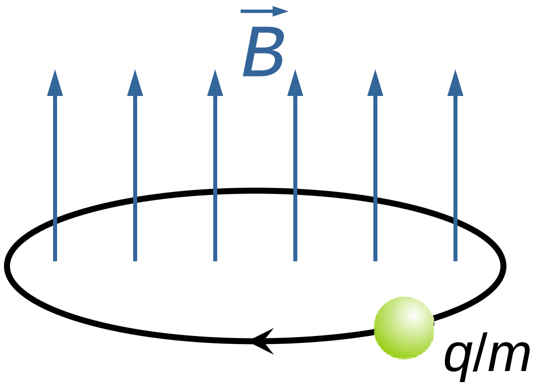
Principle of Penning trap mass spectrometry

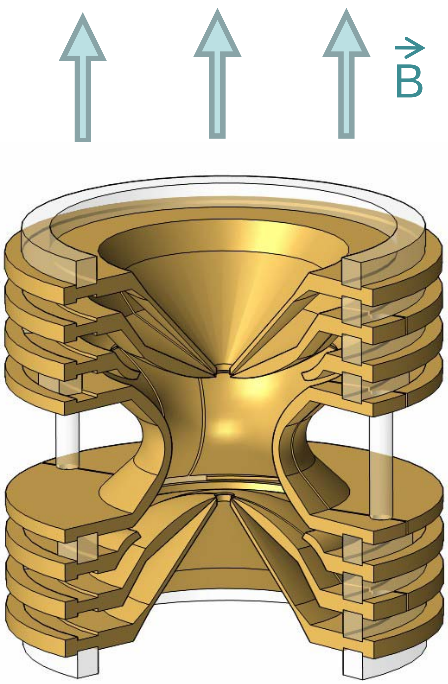


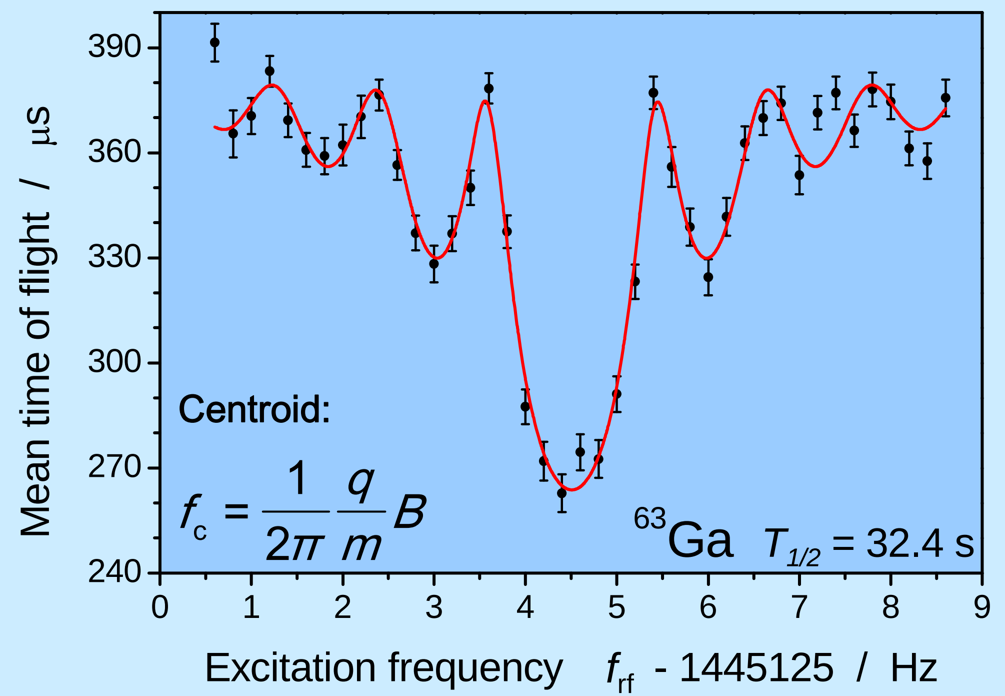
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field





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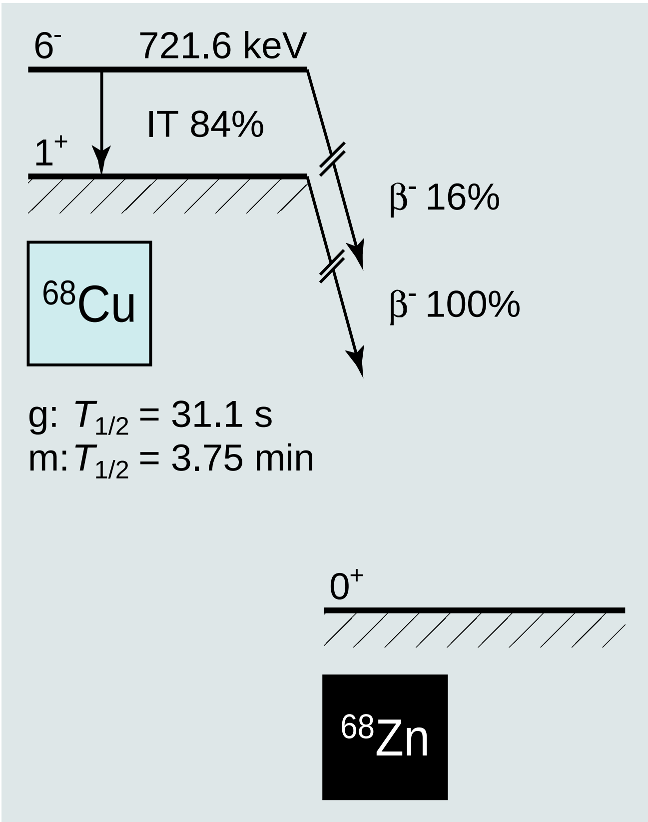
Separation of isomeric states

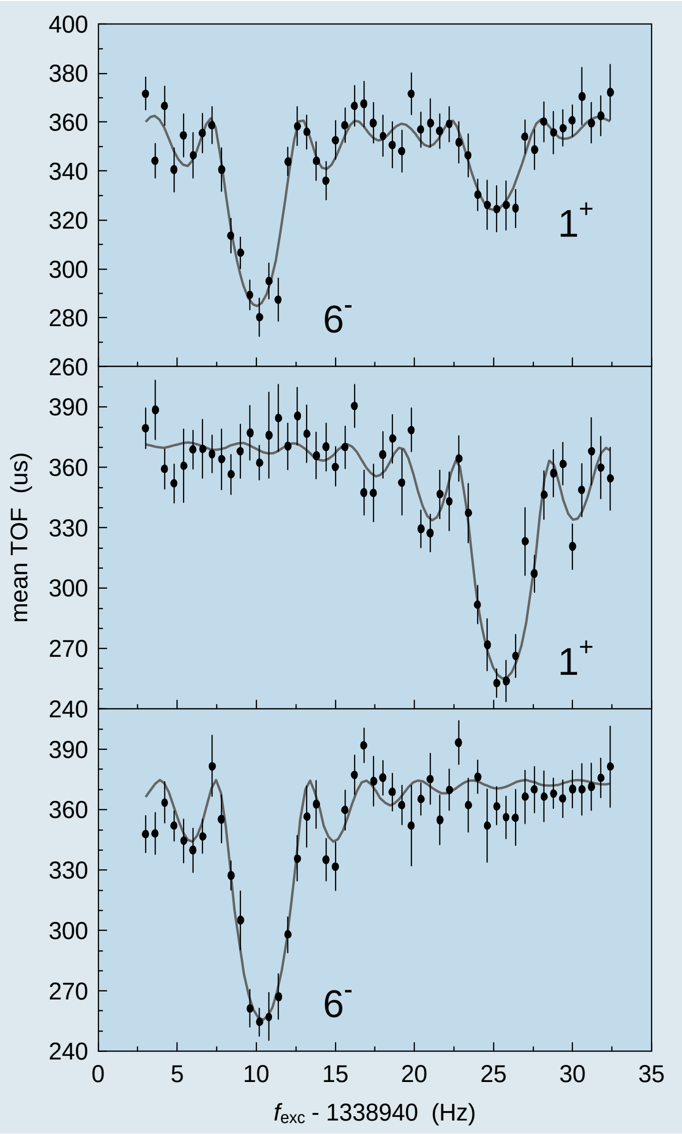
Isomerism in ^{68}Cu:



as produced by ISOLDE

isolation of the 1^+ ground state

isolation of the 6^- isomeric state



Resolving power of excitation: $R \approx 10^7$

⇒ Population inversion of nuclear states

⇒ Preparation of an isomerically pure beam

K. Blaum *et al.*, Europhys. Lett. 67, 586 (2004)

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Nuclear structure studies

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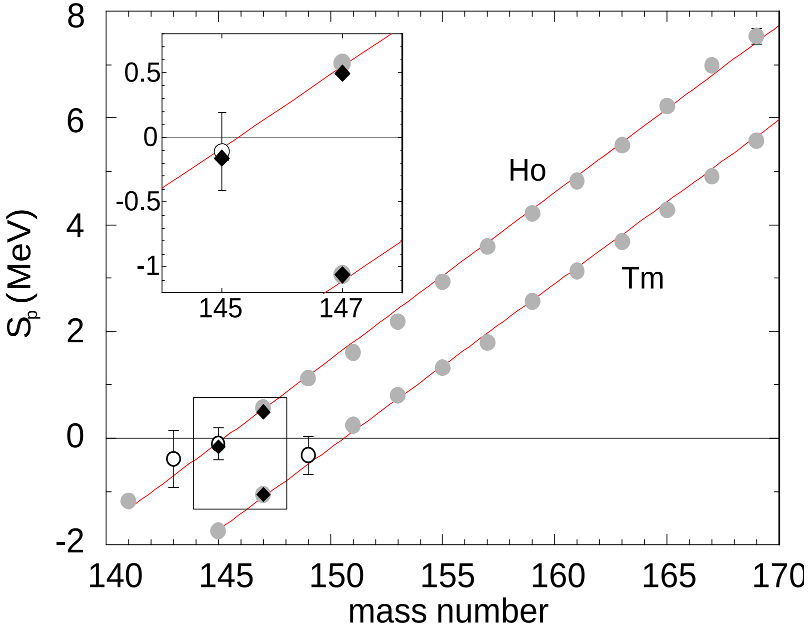
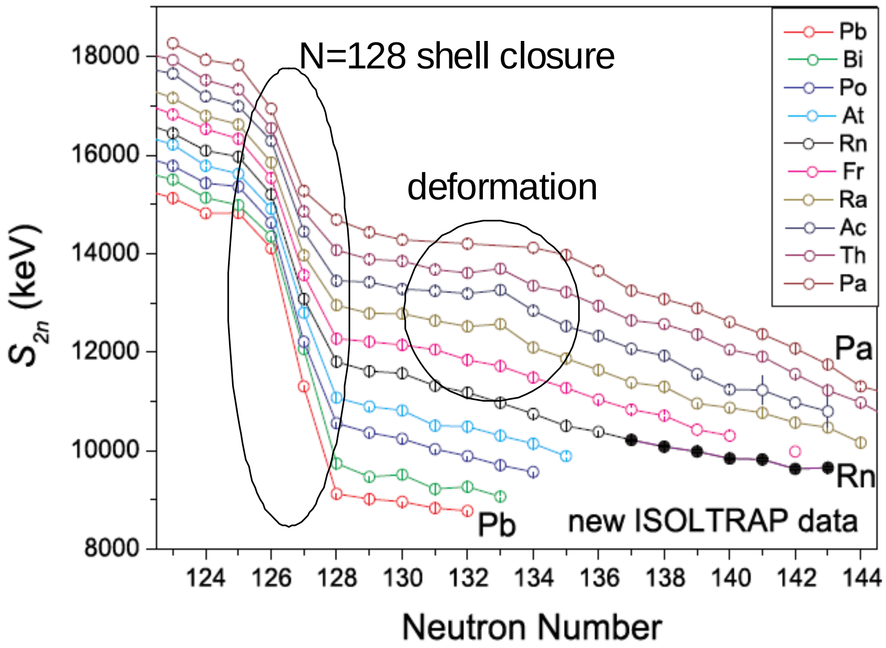
$S_p = B(Z,N) - B(Z\text{-}1,N)$



First direct mass measurement beyond the proton dripline.

$S_{2n} = B(Z,N) - B(Z,N\text{-}2)$



Investigation of shell closures, onset of deformation, collective effects.

C. Rauth *et al*., Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al*., Phys. Rev. Lett. 100, 072501 (2008)

B. Cakirli *et al*., Phys. Rev. Lett. 102, 082501 (2009)
D. Neidherr *et al*., Phys. Rev. Lett. 102, 112501 (2009)

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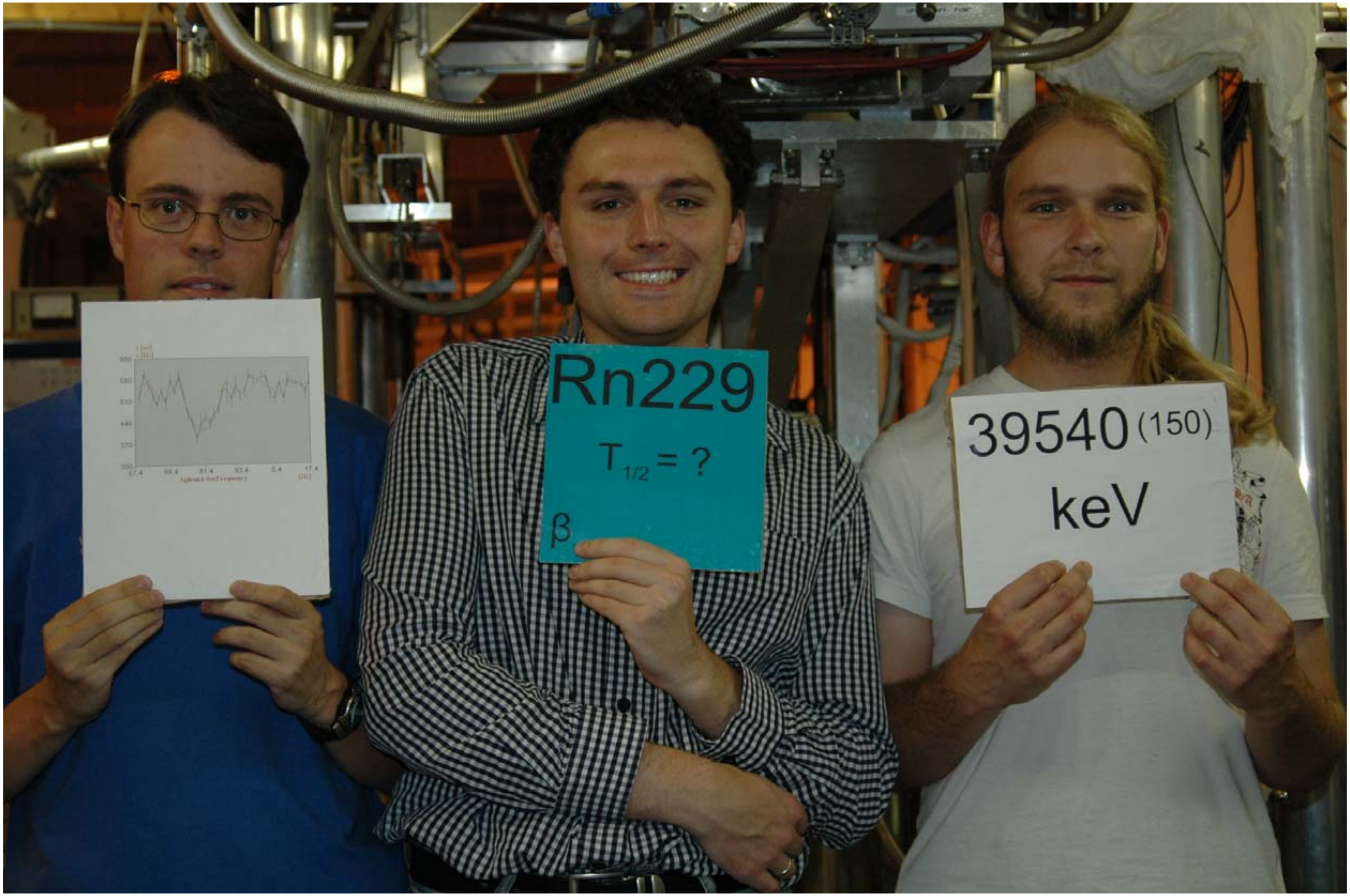
The discovery of a new isotope, ^{229}Rn



26.08.2008, 4:24 am

D. Neidherr *et al.*, Phys. Rev. Lett. 102, 112501 (2009)

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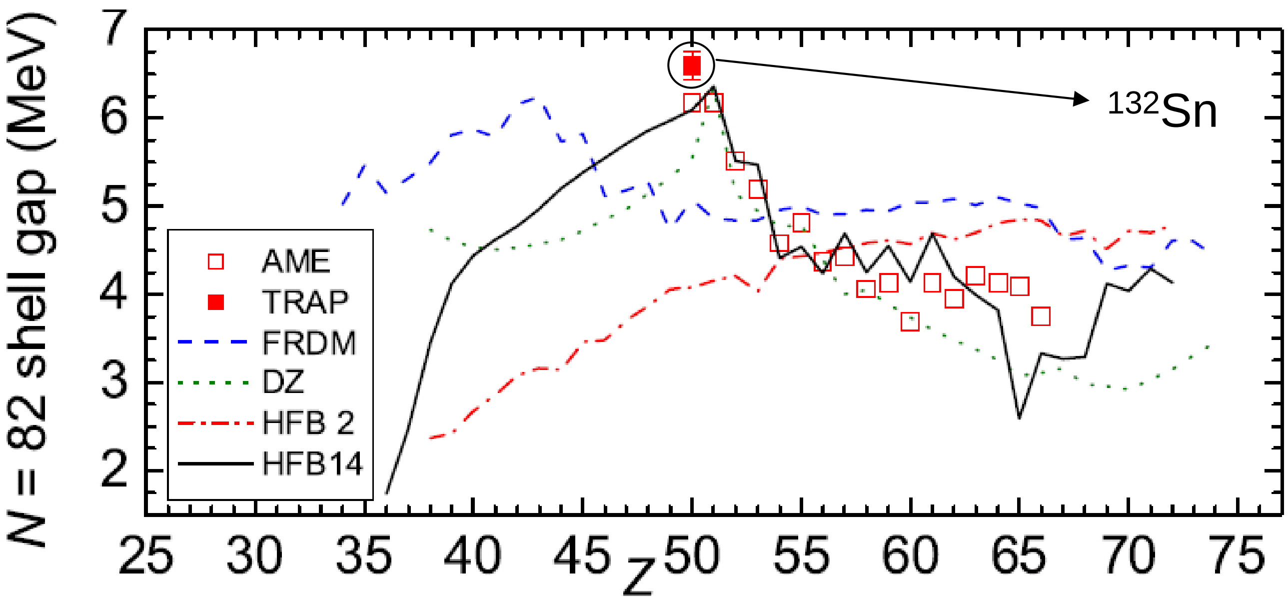
^{132,134}Sn

Magicity of N = 82

neutron shell gap $\Delta_n(N_0, Z) = S_{2n}(N_0, Z) - S_{2n}(N_0 + 2, Z)$



Restoration of *N* = 82 gap

M. Dworschak *et al*., Phys. Rev. Lett. 100, 072501 (2008)

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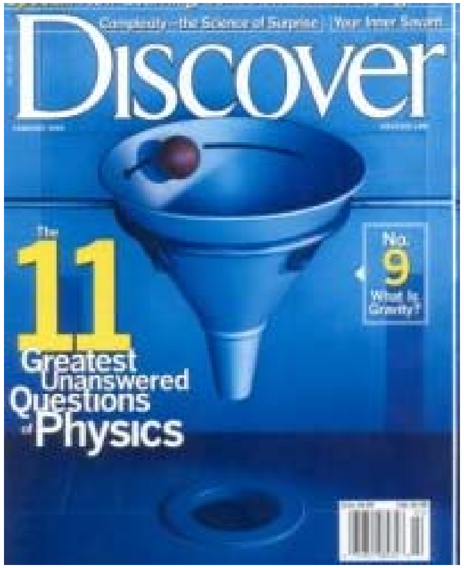
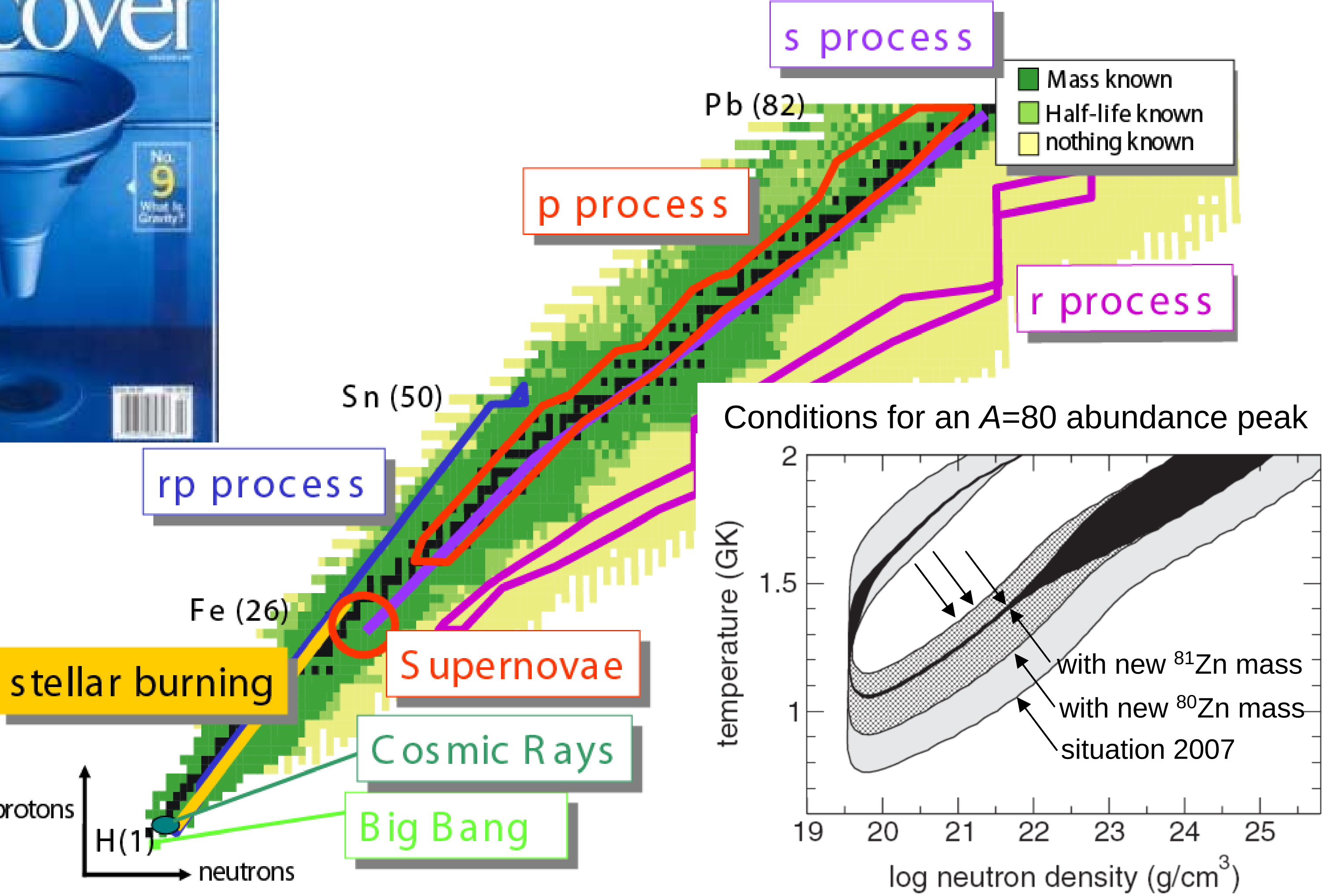
Applications in astrophysics

K. B. *et al*., Phys. J. 5, 35 (2006); H. Schatz *et al*., Europhys. News 37, 16 (2006)





M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004)
V.-V. Elomaa *et al*., Phys. Rev. Lett. 102, 252501 (2009)

D. Rodríguez *et al*., Phys. Rev. Lett. 93, 161104 (2004)
S. Baruah *et al*., Phys. Rev. Lett. 101, 262501 (2008)

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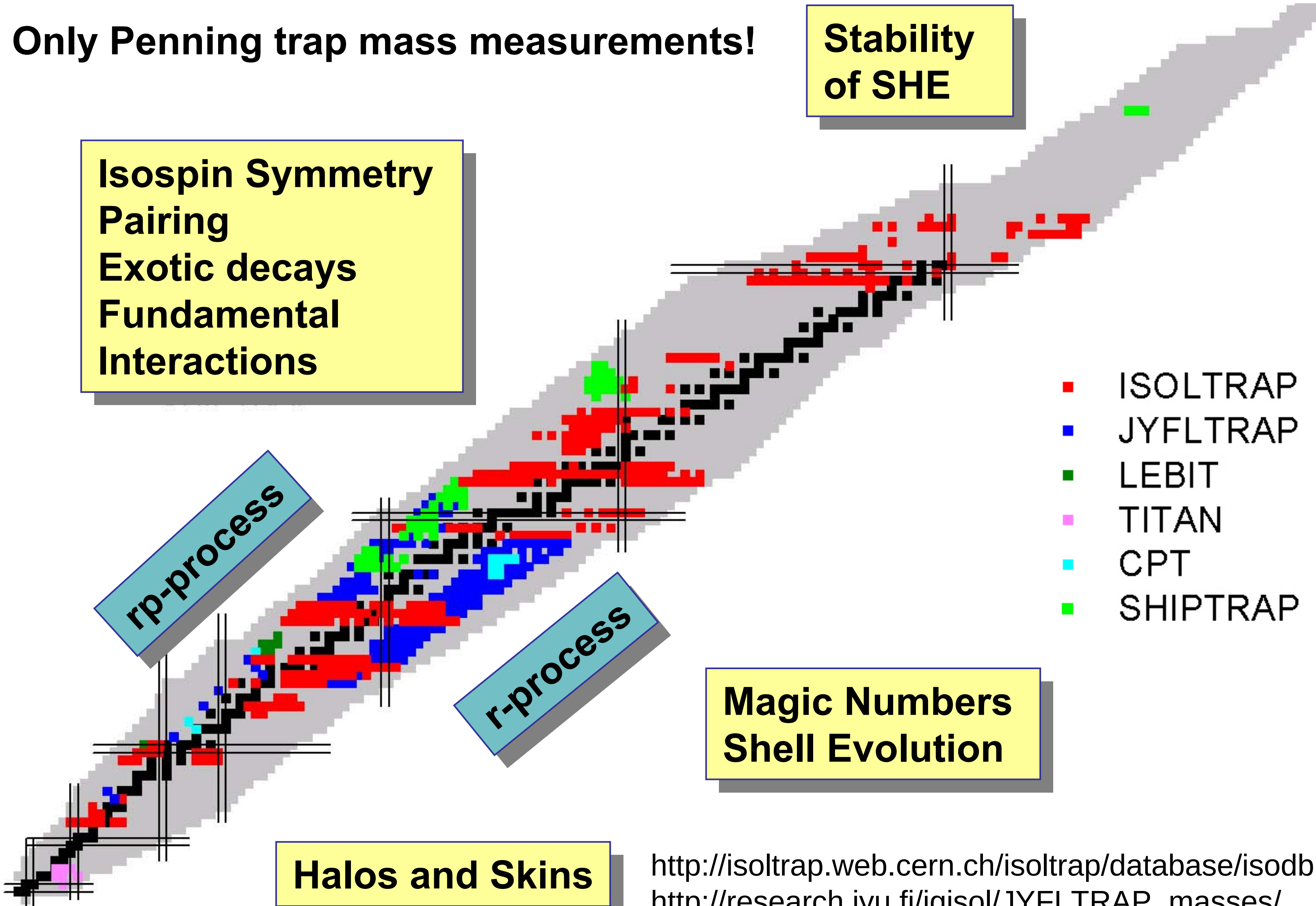
What has been done so far?

Only Penning trap mass measurements!

Stability of SHE

Isospin Symmetry
Pairing
Exotic decays
Fundamental Interactions



Magic Numbers
Shell Evolution

Halos and Skins

http://isoltrap.web.cern.ch/isoltrap/database/isodb.asp
http://research.jyu.fi/igisol/JYFLTRAP_masses/

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Summary

Precision atomic physics techniques play an important role in nuclear structure studies!

- Precise determination of atomic and nuclear ground state properties
- Investigation of nuclear halos
- Test of nuclear mass models
- Nuclear structure studies
- Weak interaction studies
- Reliable calculations in nuclear astrophysics need precision nuclear ground state data like masses **For Bob!**
- Tests of fundamental symmetries and interactions

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Thanks

Thanks a lot for the invitation and your attention!

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WWW: www.mpi-hd.mpg.de/blaum/