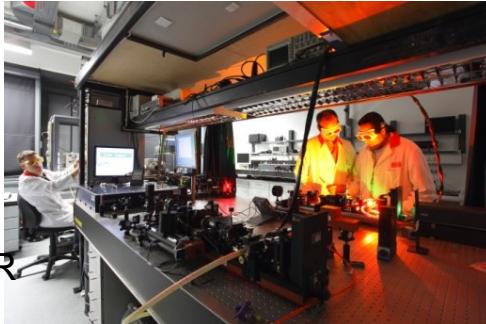


# Recent Developments in Laser Spectroscopy for RIBs



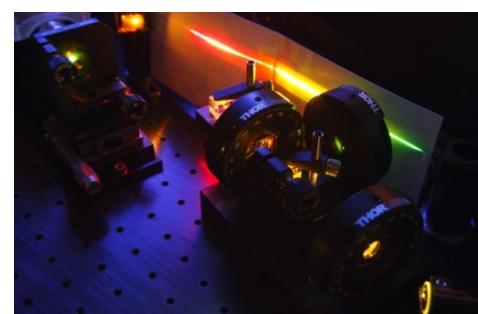
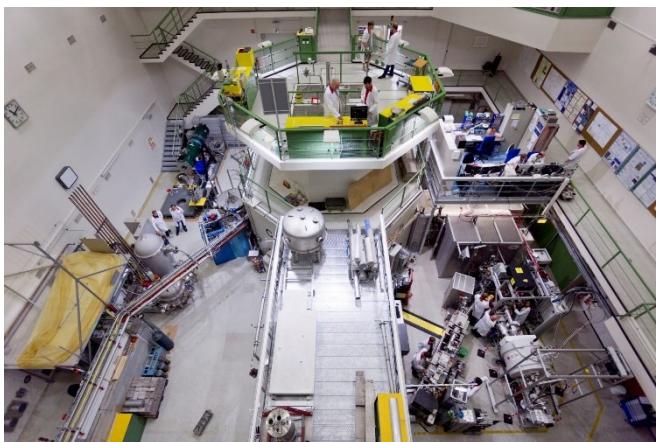
Wilfried Nörtershäuser



TRIGA-LASER  
@ Mainz



BECOLA @MSU



Frequency Comb



Forth Harmonic Generation



# Outline Lecture 1



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Isotope Shift and Hyperfine Structure – A brief introduction

Collinear Laser Spectroscopy – Basic Approach

Example 1: The „Island of Inversion“ – Spectroscopy of Mg

- Optical Detection
- Optical Pumping and  $\beta$ -Asymmetry Detection
- $\beta$ -NMR

Example 2: Halo Nuclei: Charge Radii of Be Isotopes and a  
Test of NR-QED Calculations

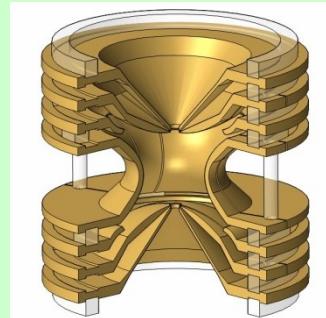
- Collinear / Anticollinear Approach



# Motivation



## Mass Spectrometry

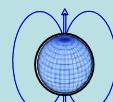


nuclear  
binding  
energy  
?



ground state  
properties of  
exotic nuclei

magnetic  
dipole  
moment

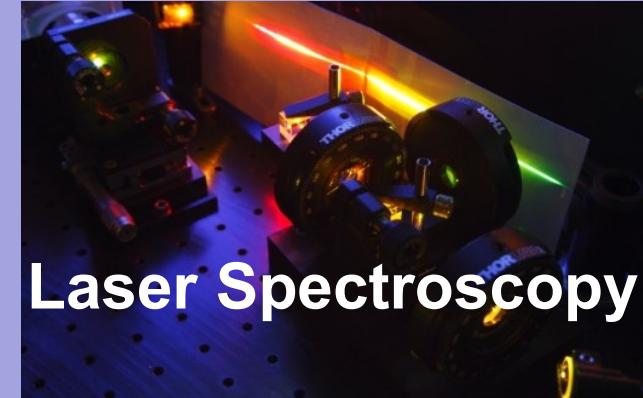
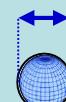


nuclear  
spin

spectroscopic  
quadrupole  
moment

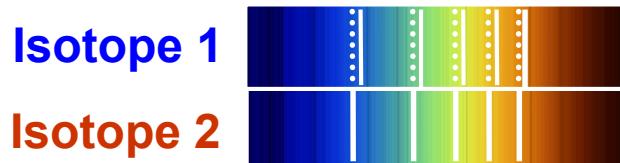


nuclear  
charge  
radius

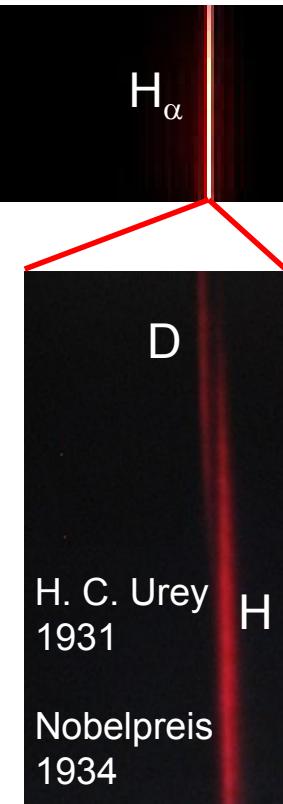
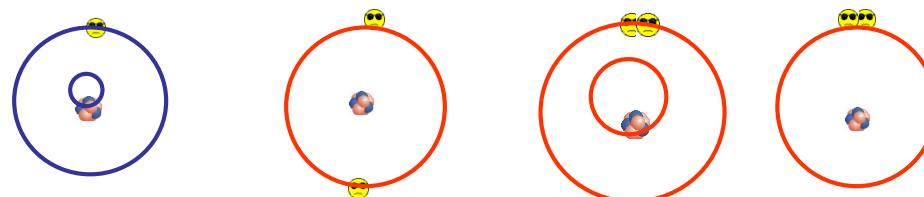


## Laser Spectroscopy

# Isotope Shift and the Nuclear Mass Effect



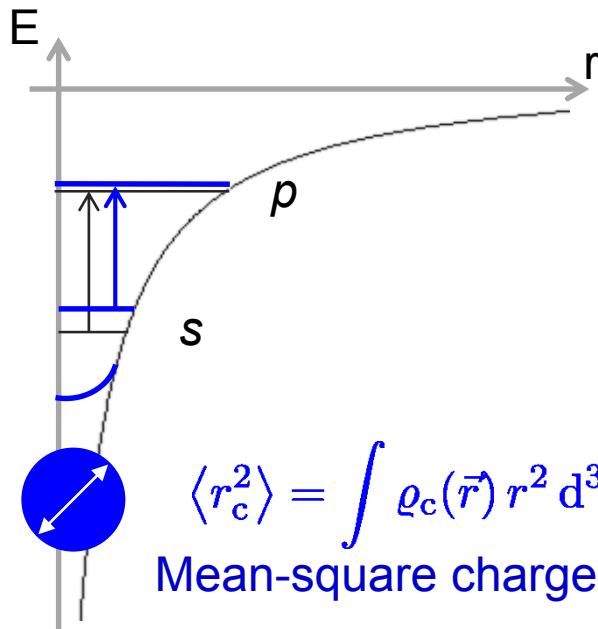
$$\delta\nu_{\text{IS}}^{AA'} = \nu^{A'} - \nu^A$$



$$\begin{aligned} \delta\nu_{\text{MS}}^{AA'} &= \delta\nu_{\text{NMS}}^{AA'} + \delta\nu_{\text{SMS}}^{AA'} \\ &= (K_{\text{NMS}} + K_{\text{SMS}}) \cdot \frac{M_{A'} - M_A}{M_A M_{A'}}. \end{aligned}$$

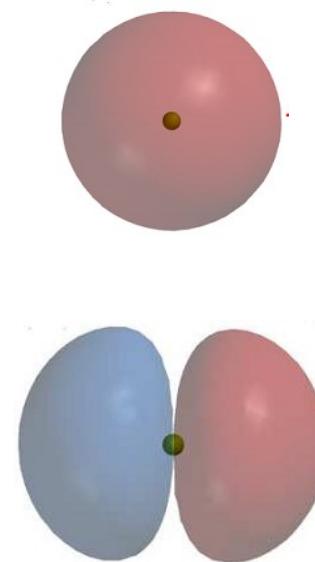
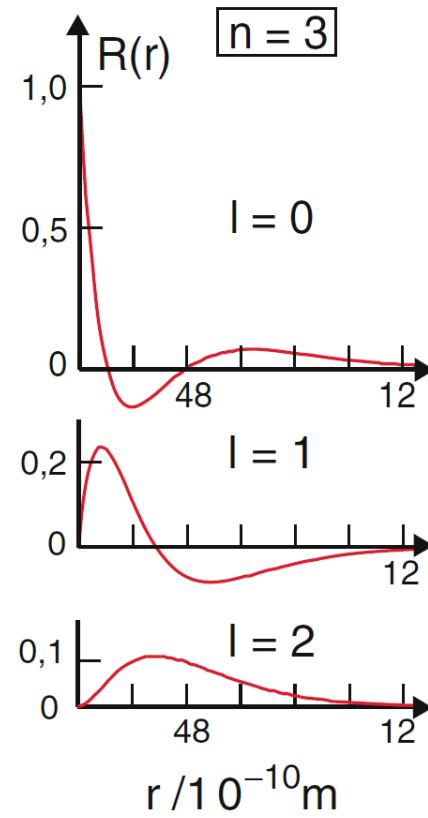
$K_{\text{NMS}} = \nu_0 \cdot m_e$



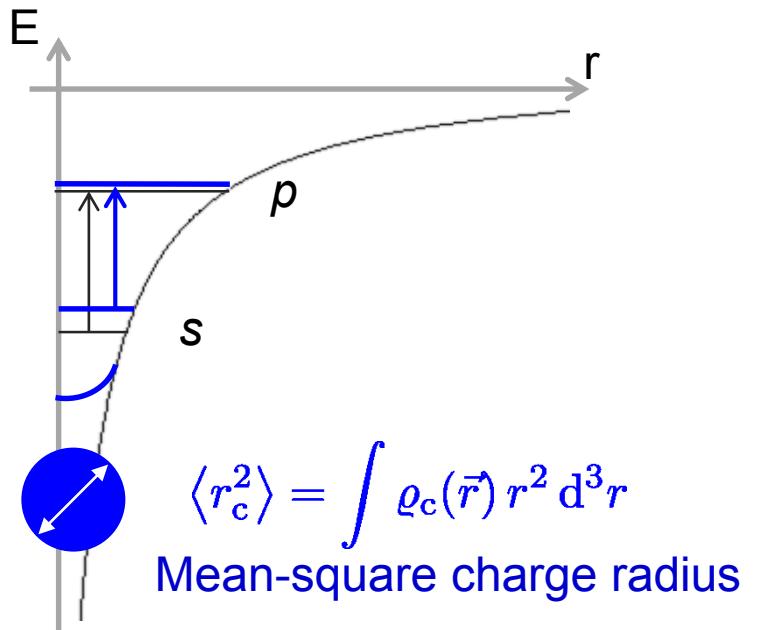


$$\delta\nu_{\text{FS}} = -\frac{Ze^2}{6\epsilon_0} \underbrace{\Delta |\Psi_e(0)|_{i \rightarrow f}^2}_{\text{Electronic Factor}} \times \underbrace{\langle r_c^2 \rangle}_{\text{Nuclear Size}}$$

$$= F_{i \rightarrow f} \langle r_c^2 \rangle$$

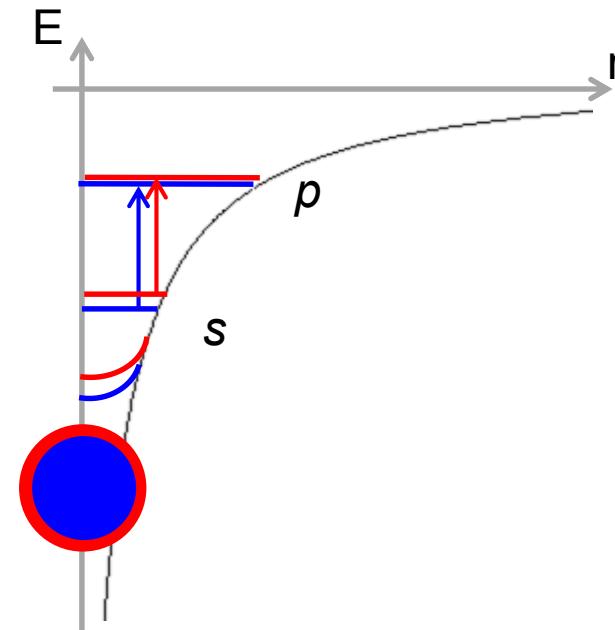


# Field Shift (Finite Nuclear Size Effect)



$$\delta\nu_{\text{FS}} = \underbrace{-\frac{Ze^2}{6\epsilon_0} \Delta |\Psi_e(0)|_{i \rightarrow f}^2}_{\text{Electronic Factor}} \times \underbrace{\langle r_c^2 \rangle}_{\text{Nuclear Size}}$$

$$= F_{i \rightarrow f} \langle r_c^2 \rangle$$



$$\begin{aligned} \delta\nu_{\text{FS}}^{AA'} &= F_{i \rightarrow f} \left( \langle r_c^2 \rangle^{A'} - \langle r_c^2 \rangle^A \right) \\ &= F_{i \rightarrow f} \boxed{\delta \langle r_c^2 \rangle^{AA'}} \end{aligned}$$

Observable:  
Change in mean-square  
charge radius



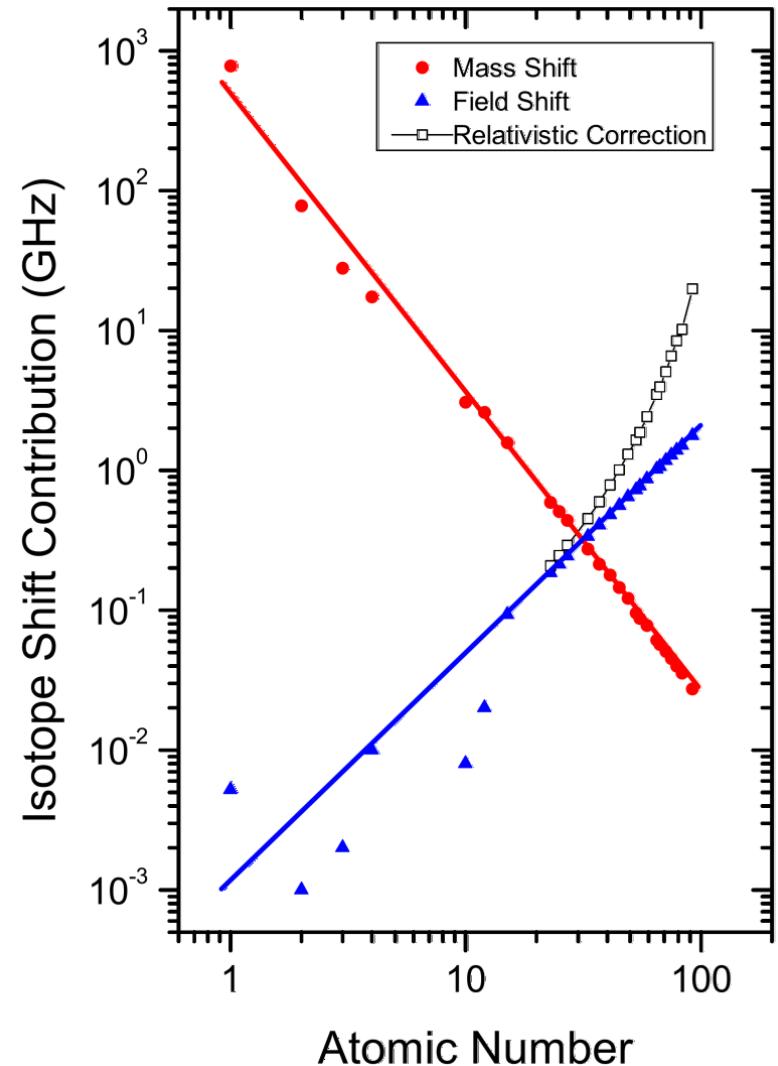
# Mass Dependence of Mass and Field Shift

$$\delta\nu_{\text{IS}}^{AA'} = \nu^{A'} - \nu^A$$

$$\delta\nu_{\text{IS}}^{AA'} = K_{\text{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + F \delta \langle r_c^2 \rangle^{AA'}$$

$$\delta\nu_{\text{MS}}^{AA'} \propto \frac{1}{M_A^2}$$

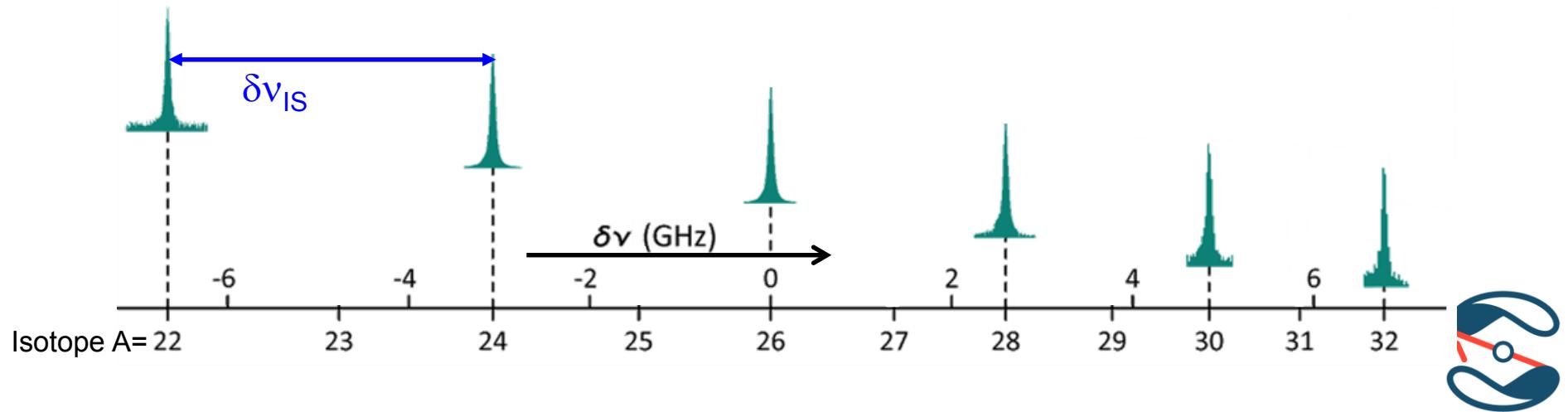
$$\delta\nu_{\text{FS}}^{AA'} \propto \frac{Z^2}{\sqrt[3]{A}}$$



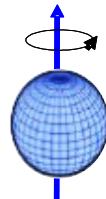
# Hyperfine Structure and Moments



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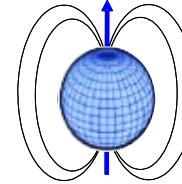
# Hyperfine Structure and Moments



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

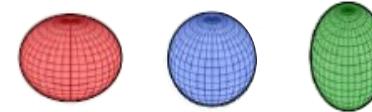
$$C = F(F+1) - I(I+1) - J(J+1)$$

Spin I



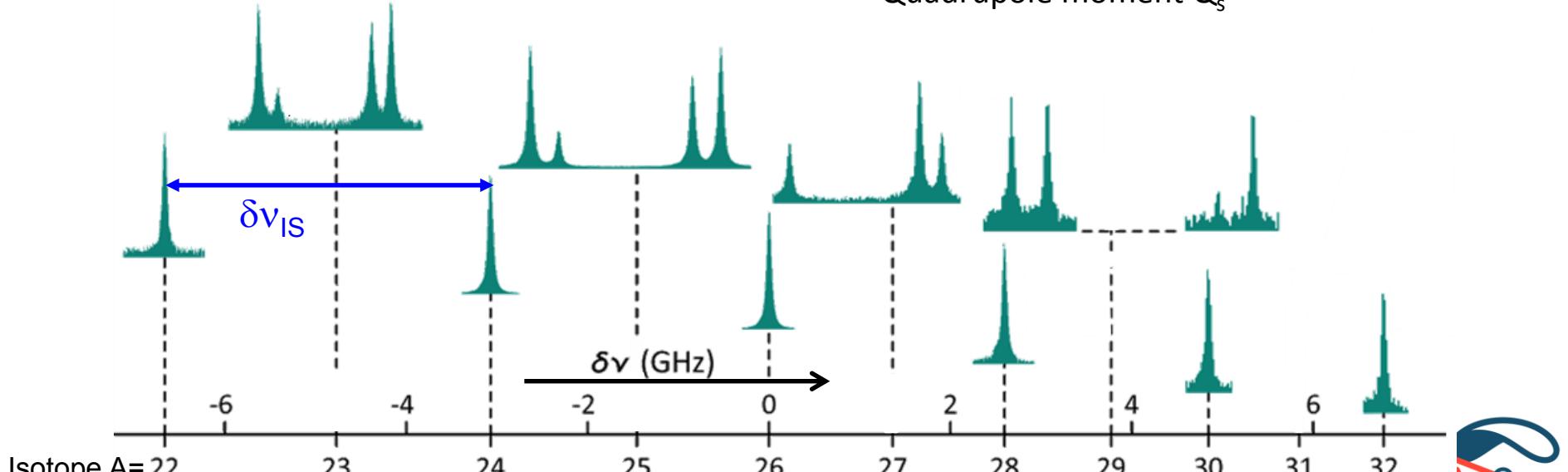
$$A = \frac{\mu_I B_e(0)}{IJ}$$

Magnetic moment  $\mu$

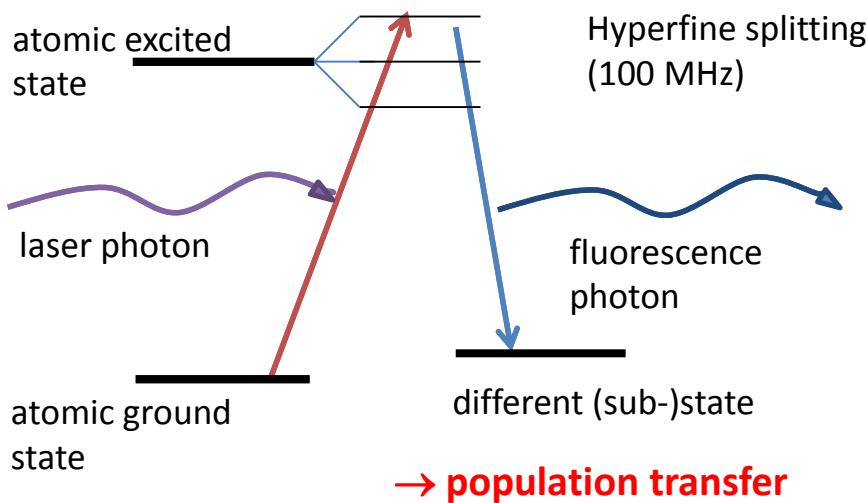
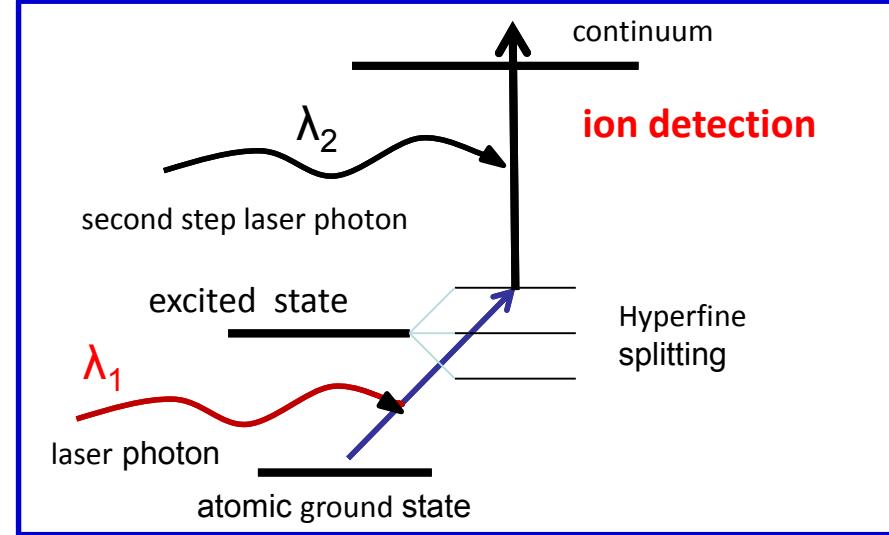
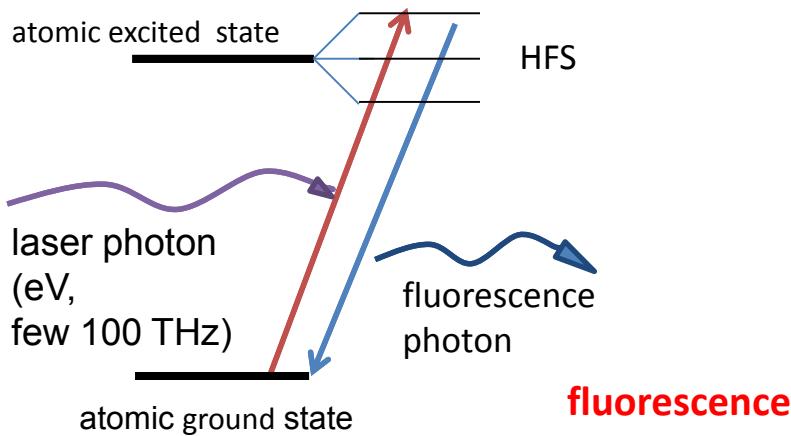


$$B = eQ_s V_{zz}$$

Quadrupole moment  $Q_s$



# Types of On-Line Laser Spectroscopy



- detect change of atomic property**
- polarized nuclei
  - charge exchange cross section
  - collisional ionization cross section
  - laser ionization cross section
  - ...



# Recent Laser Spectroscopic Work on Ground State Properties



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Heavy Elements: Th-Isomer, Ra, Fr (Parity Violation, EDM),  
(ISOLDE: CRIS, Tri $\mu$ p, TRIUMF)  
Beyond Z=100 (SHIP)

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

Monopole Migration of SPE  
due to Tensor Force (ISOLDE)  
 $N=Z$ ,  $^{74}\text{Rb}$   
CKM-Unitarity  
(TRIUMF)

Simple Structure in Complex Nuclei  
(ISOLDE)

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

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

Island of Inversion (ISOLDE)

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

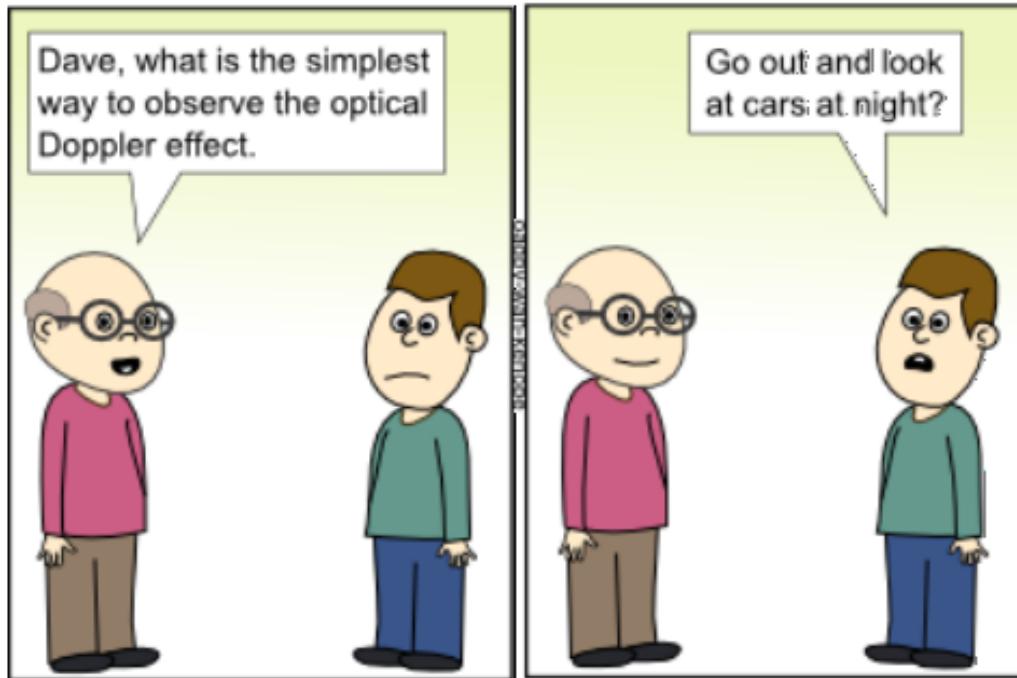
Neutron Number

not complete ...

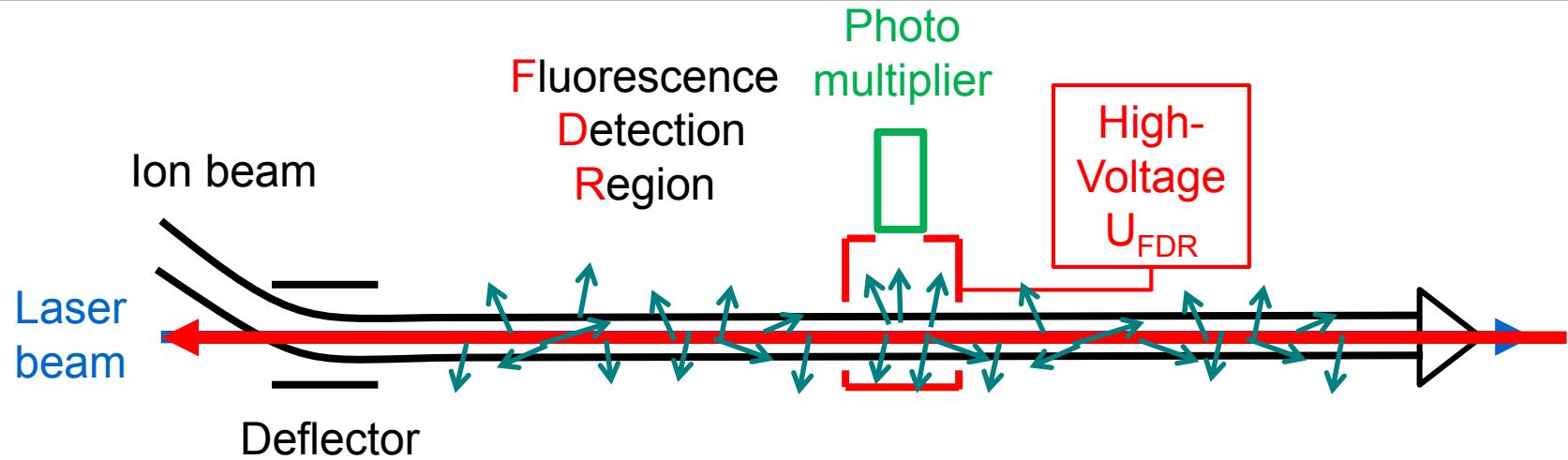
# The Optical Doppler Effect



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# The Principle Setup of Collinear Spectroscopy



Collinear Doppler shift:

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

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

Anticollinear Doppler shift:

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

Resonance condition:

$$\nu_{\text{ion}} = \nu_0$$

Doppler-Tuning:

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

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

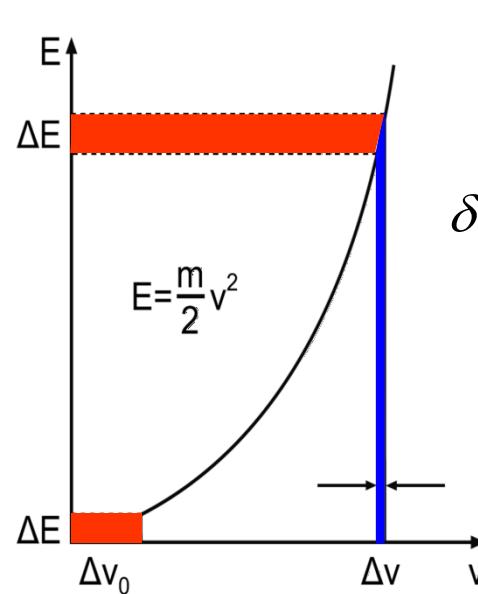
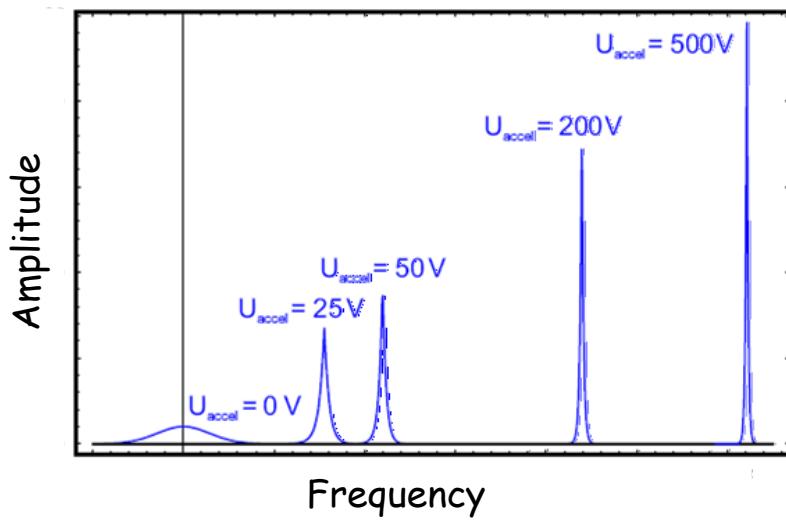
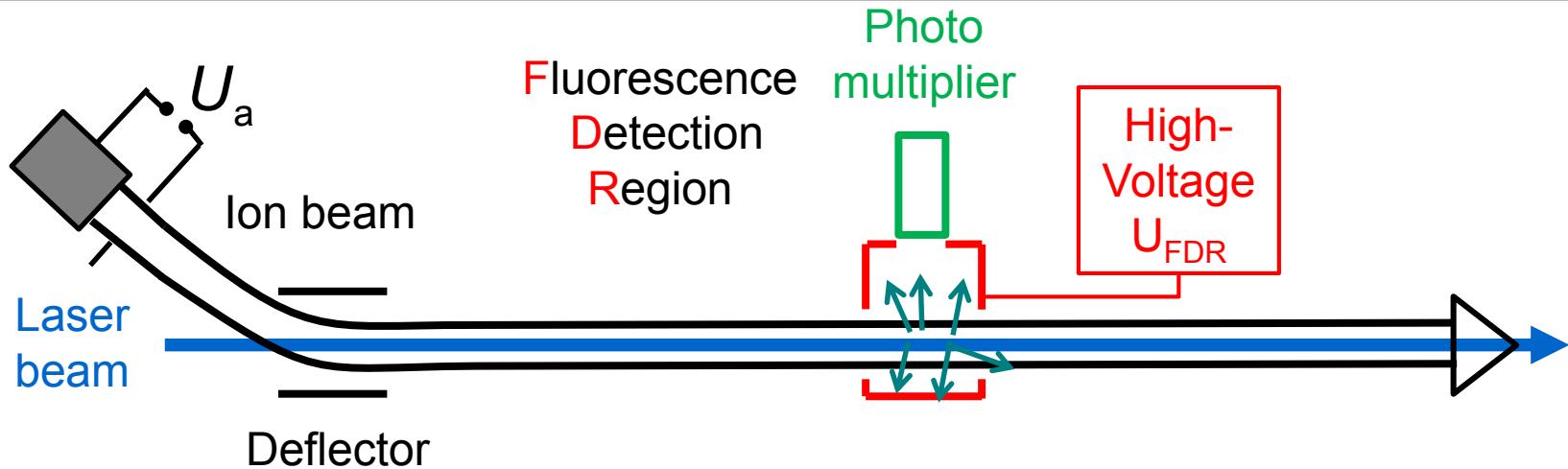
$$\frac{\partial \nu_{\text{ion}}}{\partial U} = \frac{e \nu_0}{\sqrt{2eUMc^2}}$$



# The Principle Setup of Collinear Spectroscopy



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$$E = eU_a = \frac{1}{2}mv^2$$

$$\delta E = mv \delta v$$

$$\delta v_{\text{Doppler}} = v_0 \delta v / c$$

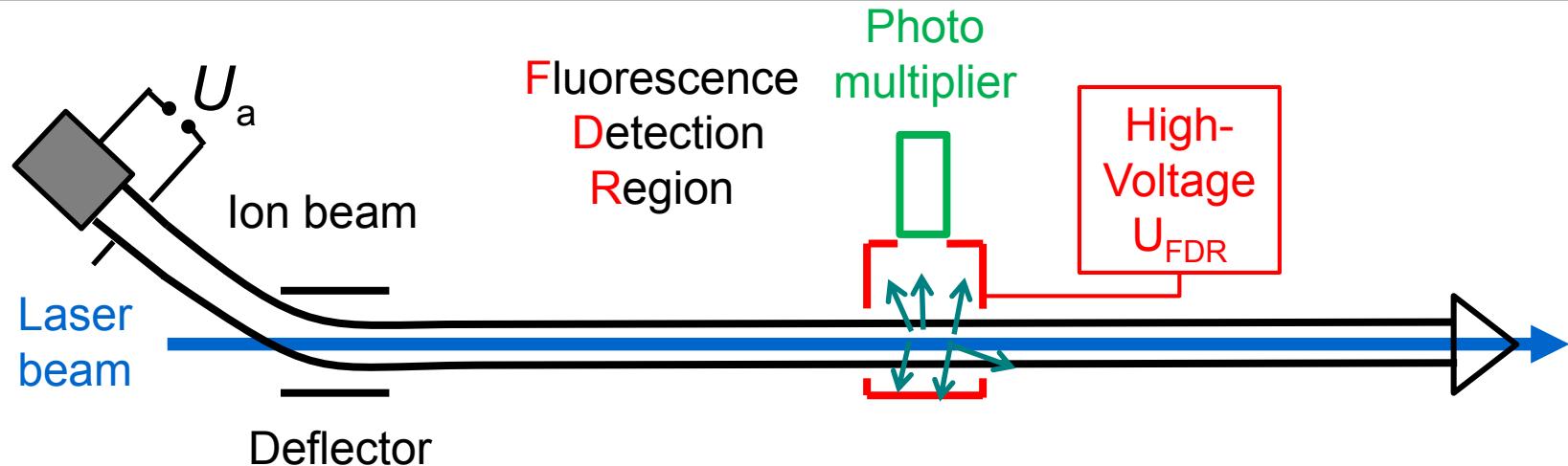
$$= v_0 \frac{\delta E}{\sqrt{2eU_a m c^2}}$$



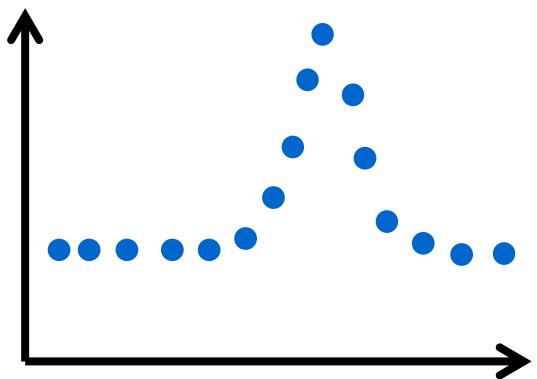
# Data Taking in Collinear Laser Spectroscopy



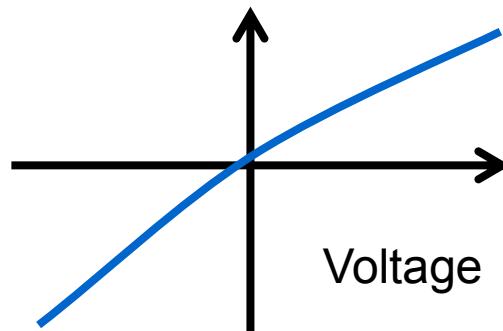
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Count rate



Frequency

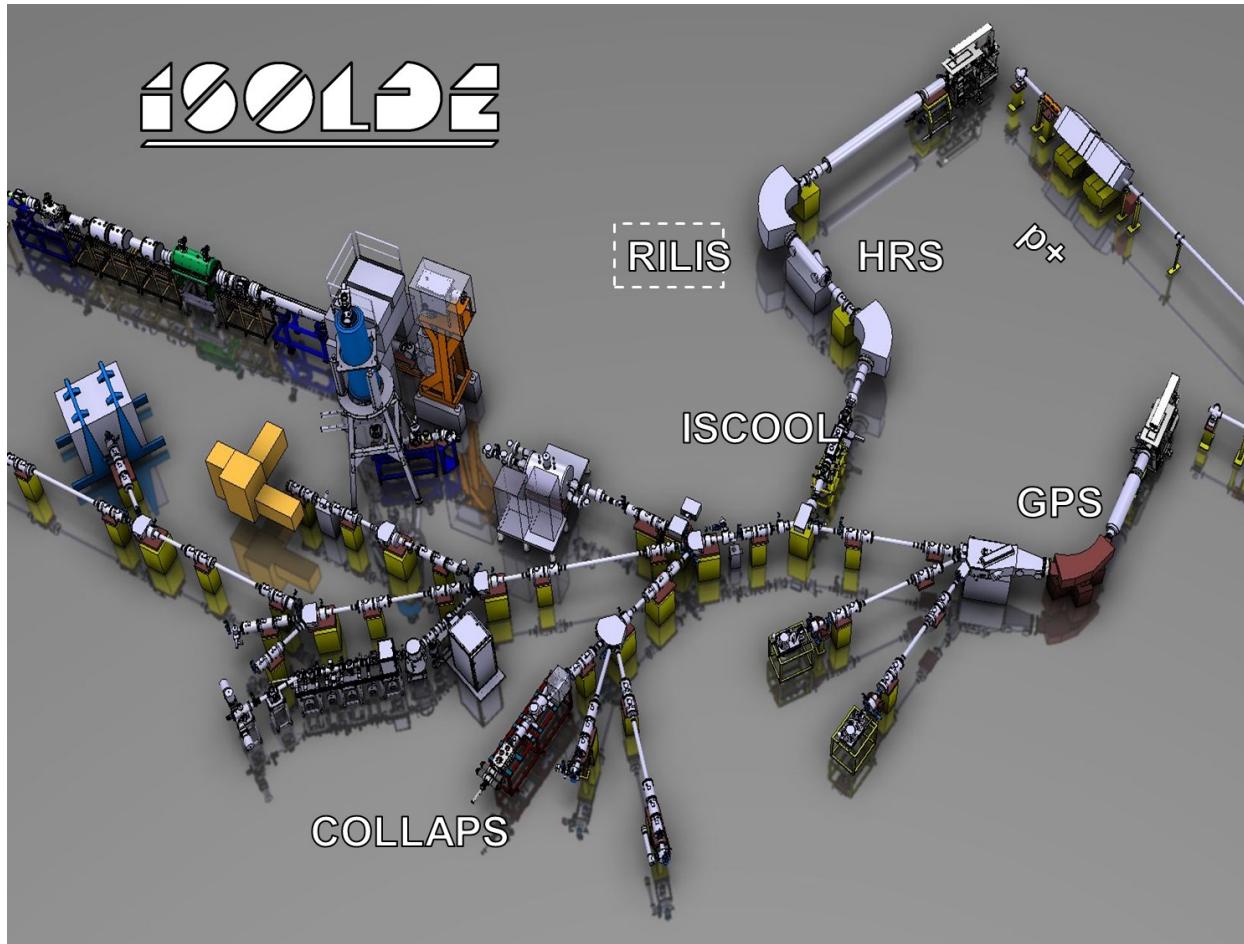


- universal
- fast
- sensitive
- high resolution





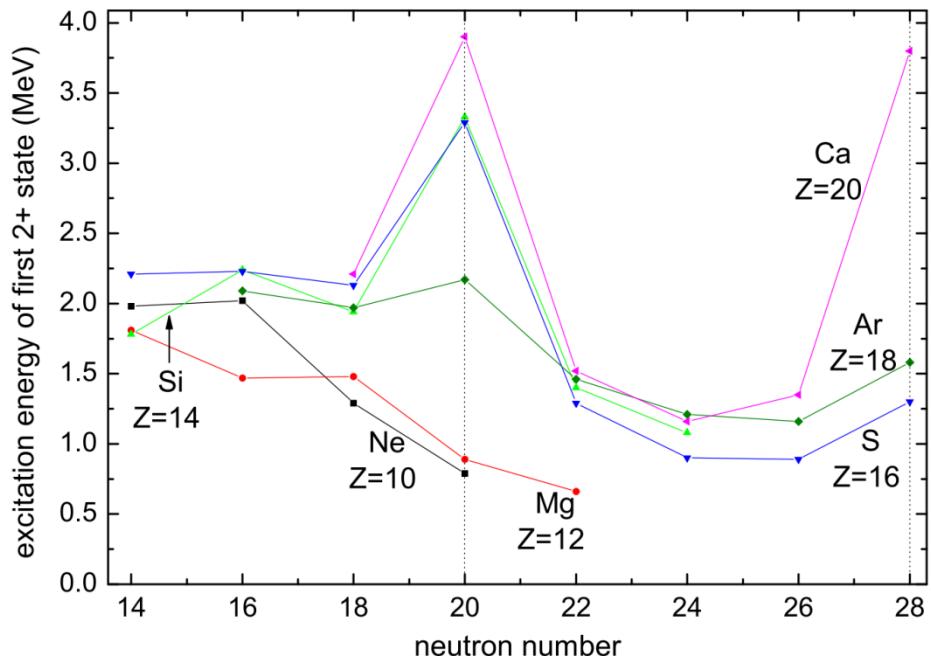
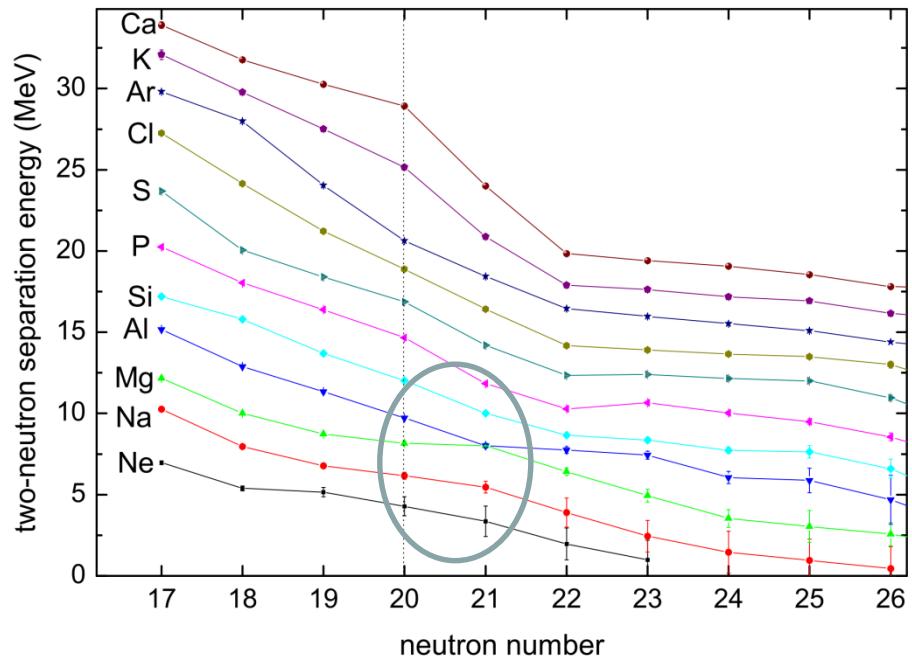
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# The Island of Inversion



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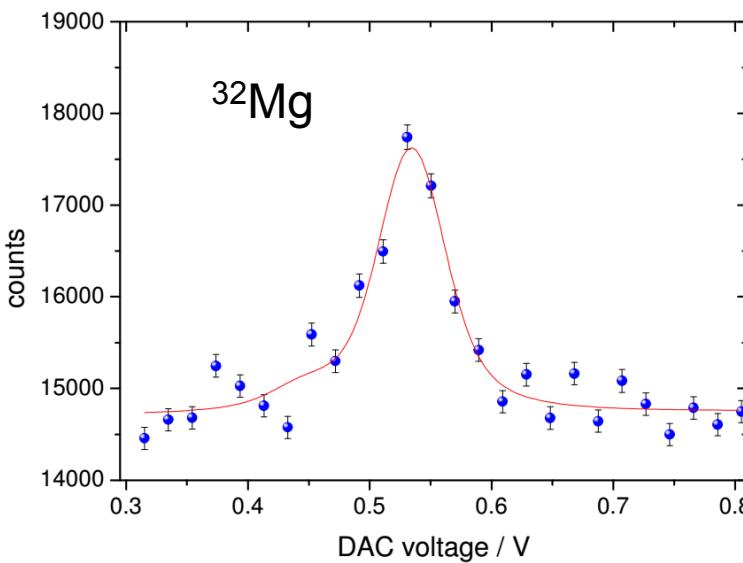
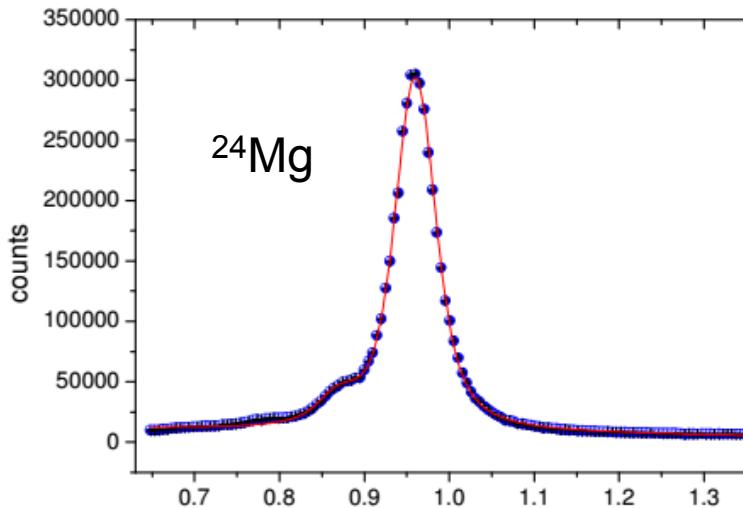
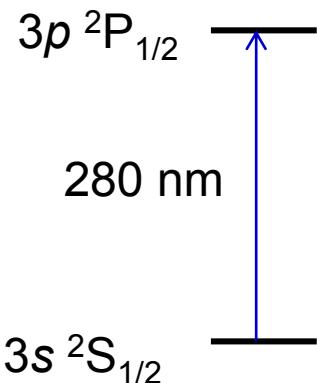
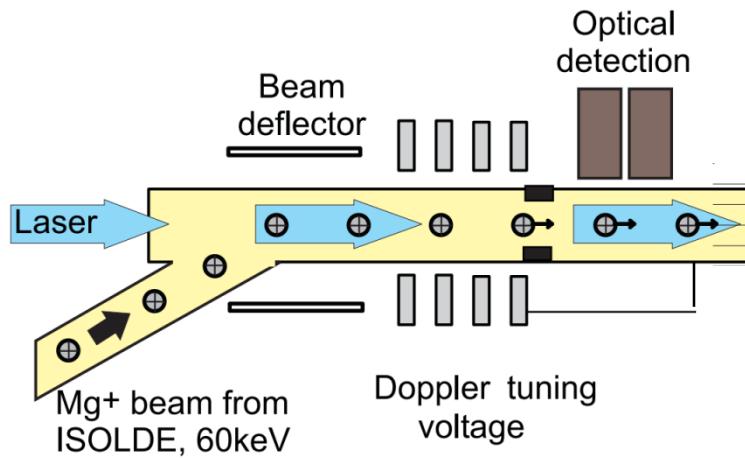
Figures taken from M. Kowalska, Dissertation, Universität Mainz (2006)



# Optical Detection: Even Isotopes



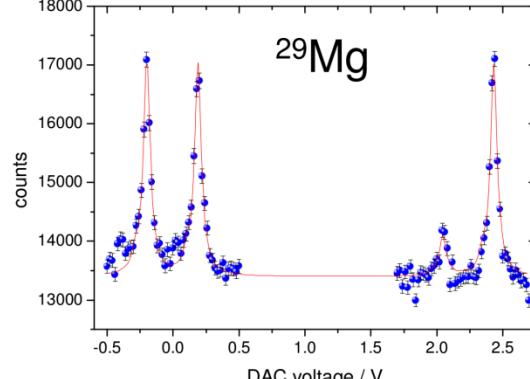
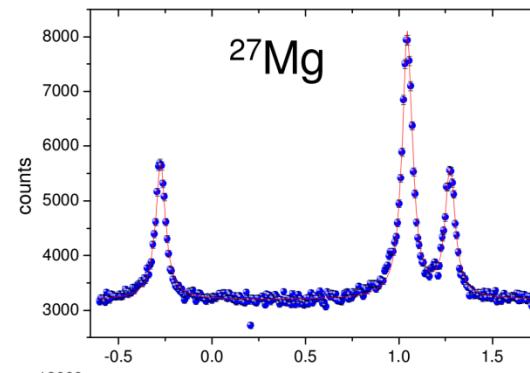
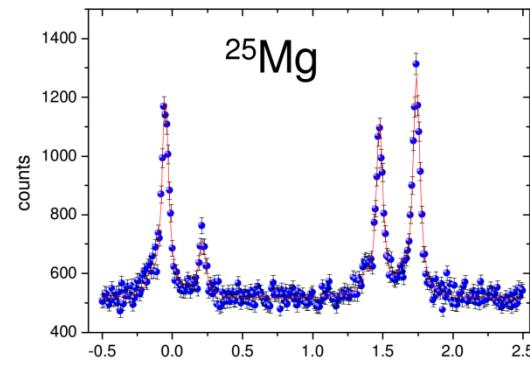
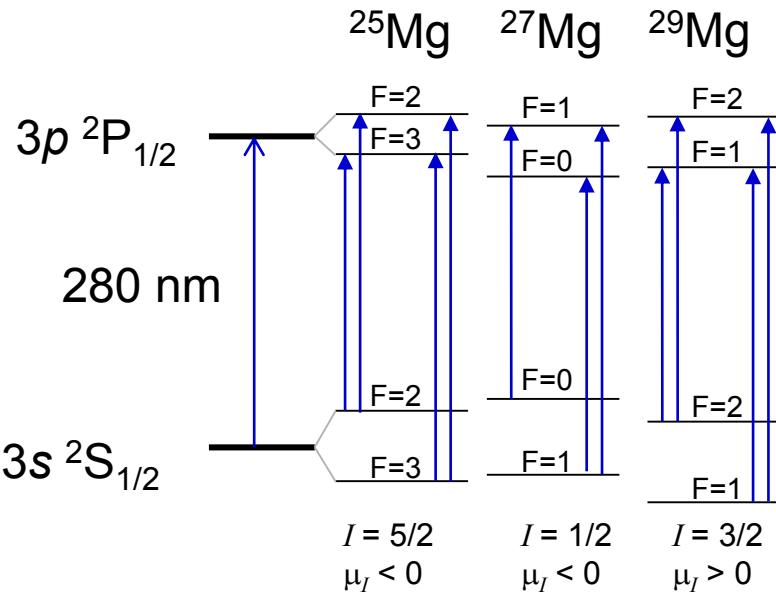
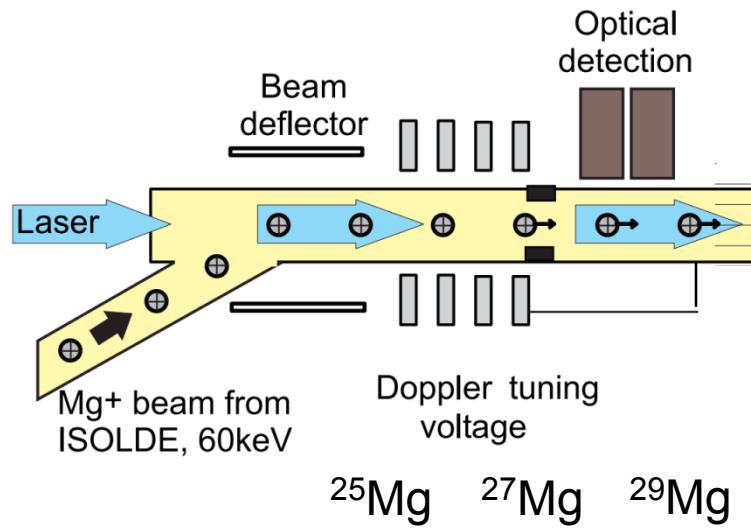
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# Optical Detection: Odd Isotopes



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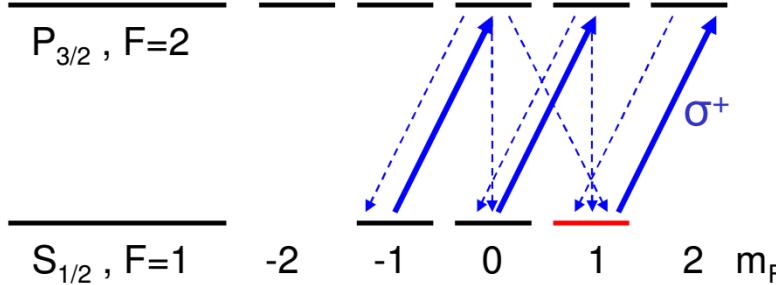
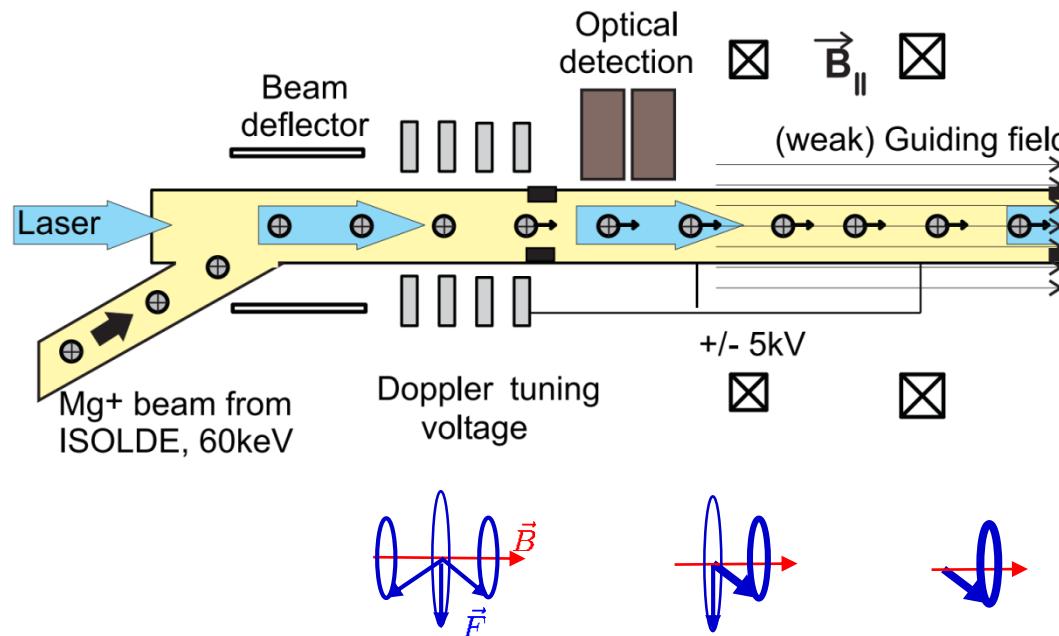
$2p\ ^3/2$	(4)
$28$	
$1f\ ^7/2$	(8)
$20$	
$1d\ ^3/2$	(4)
$2s\ ^1/2$	(2)
$1d\ ^5/2$	(6)
$8$	
$1p\ ^1/2$	(2)
$1p\ ^3/2$	(4)
$2$	
$1s\ ^1/2$	(2)
$V_{WS,SO}$	



# Optical Pumping



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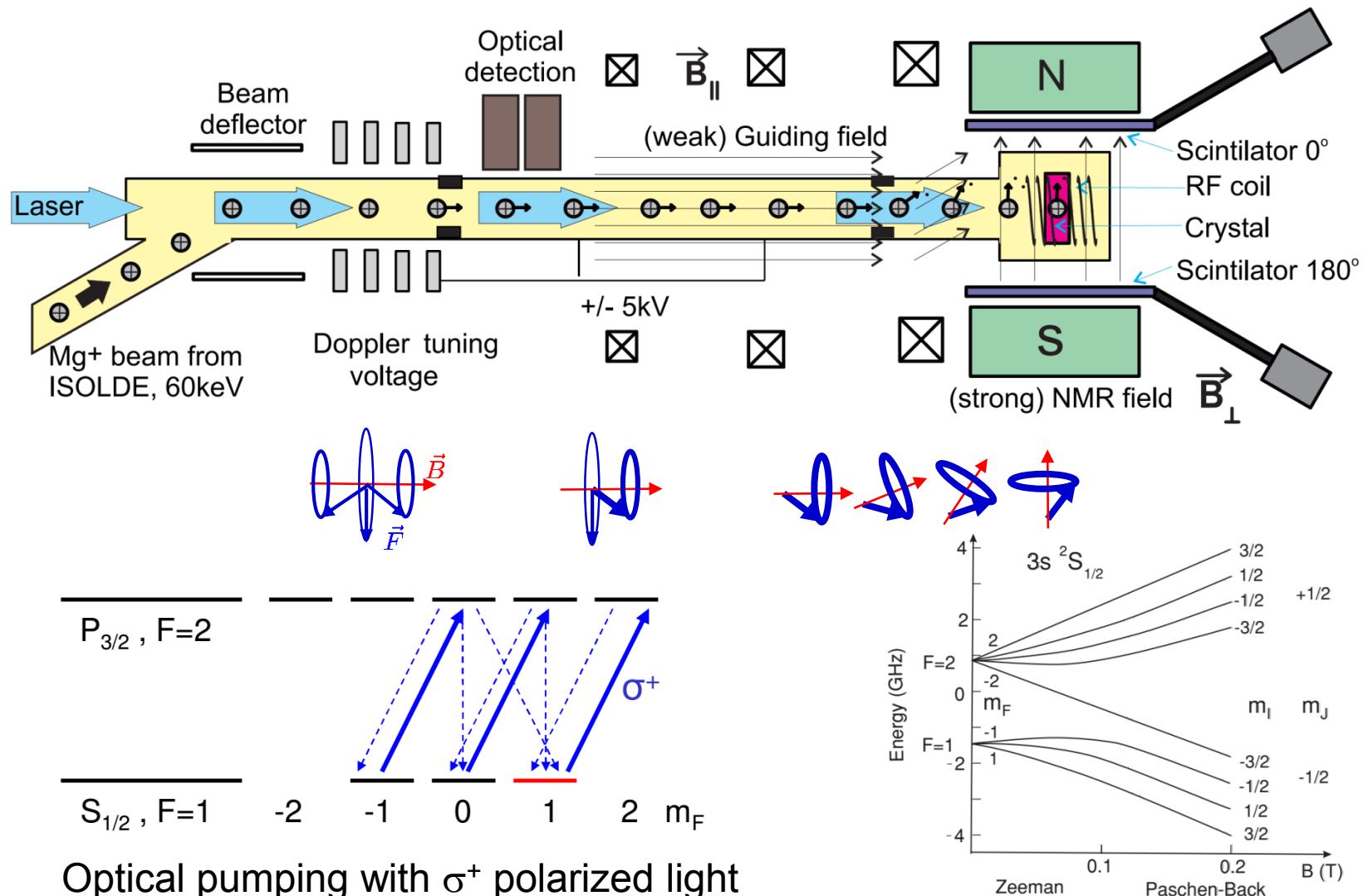
Optical pumping with  $\sigma^+$  polarized light



# Optical Pumping



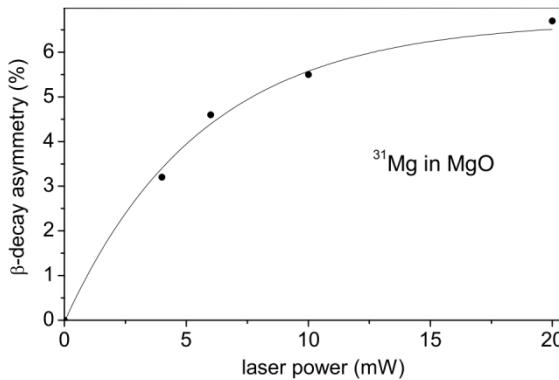
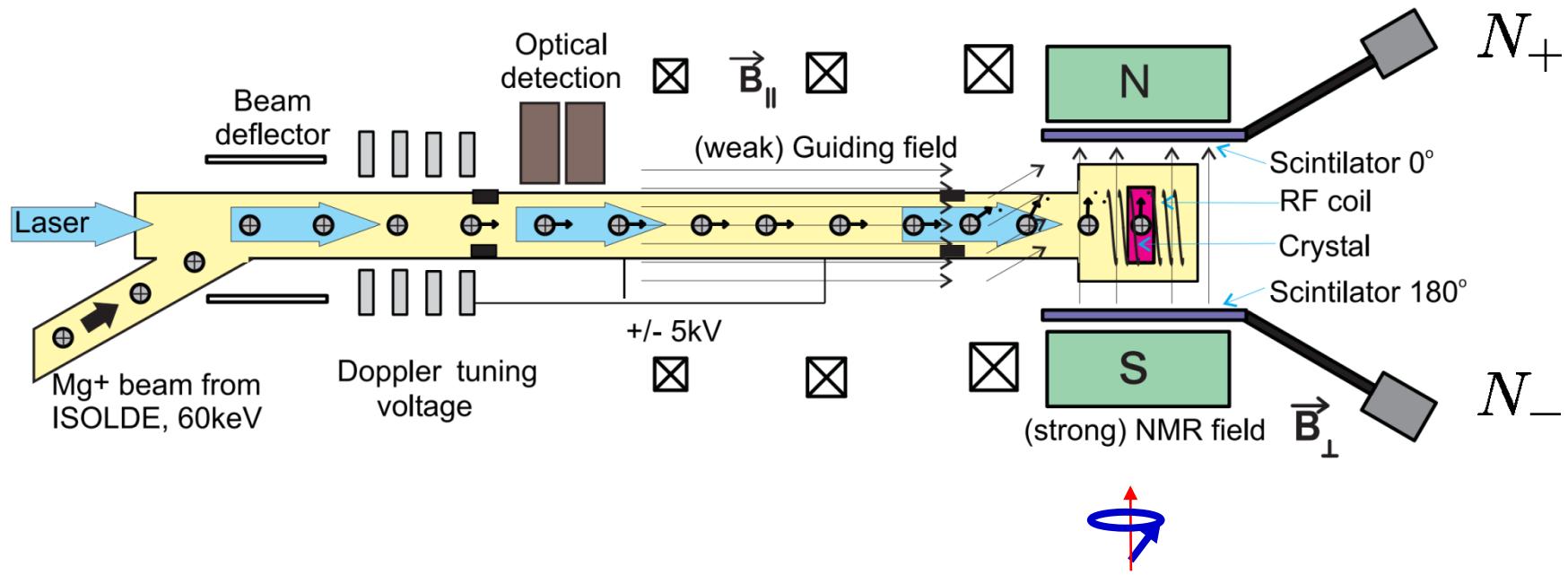
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# $\beta$ -Asymmetry Detection

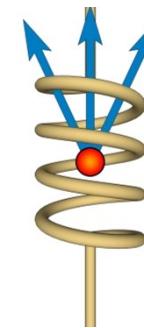


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Nuclei have a preferred direction for  $\beta$ -particle emission with respect to their spin axis (Parity Violation).

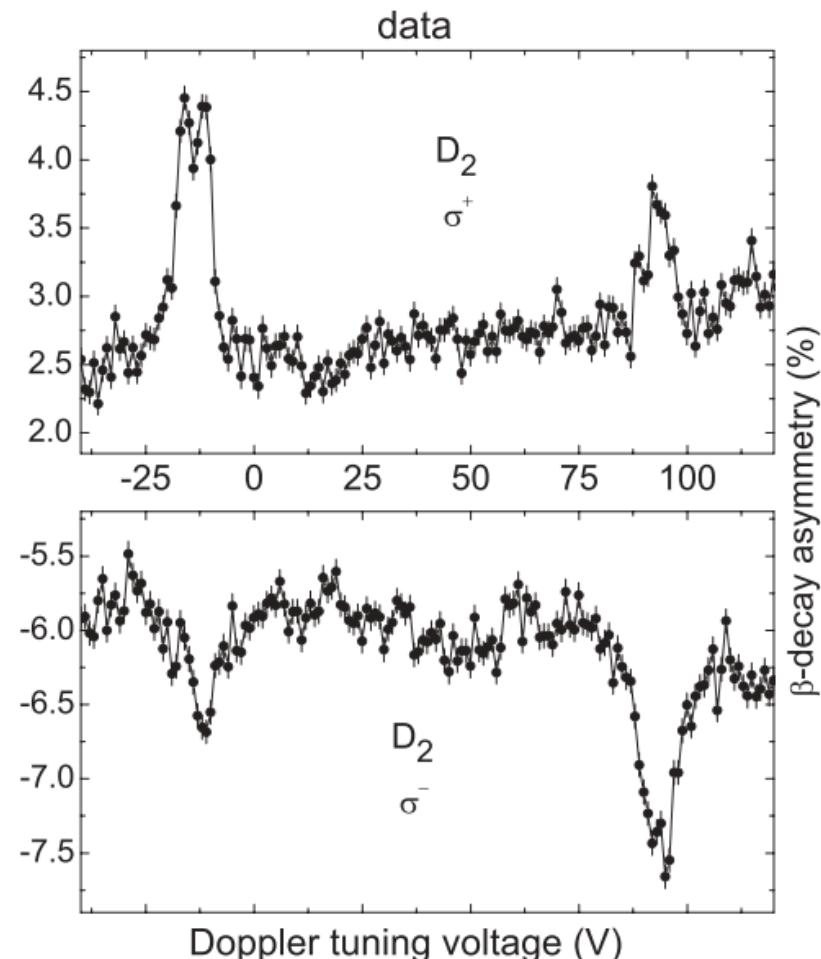
Polarization  $\rightarrow$   $\beta$ -Asymmetry



$$\frac{N_+ - N_-}{N_+ + N_-}$$

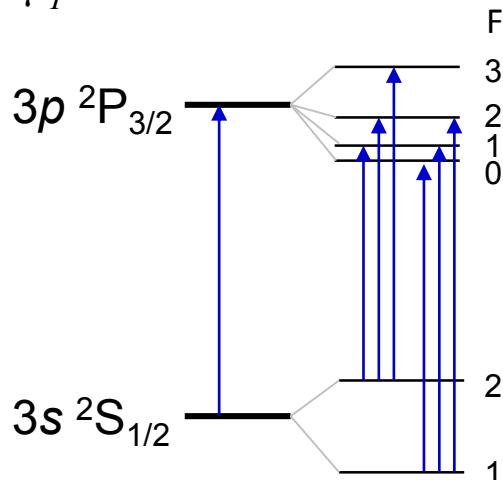


# $\beta$ -Asymmetry Detection of $^{29}\text{Mg}$



$$I = 3/2$$

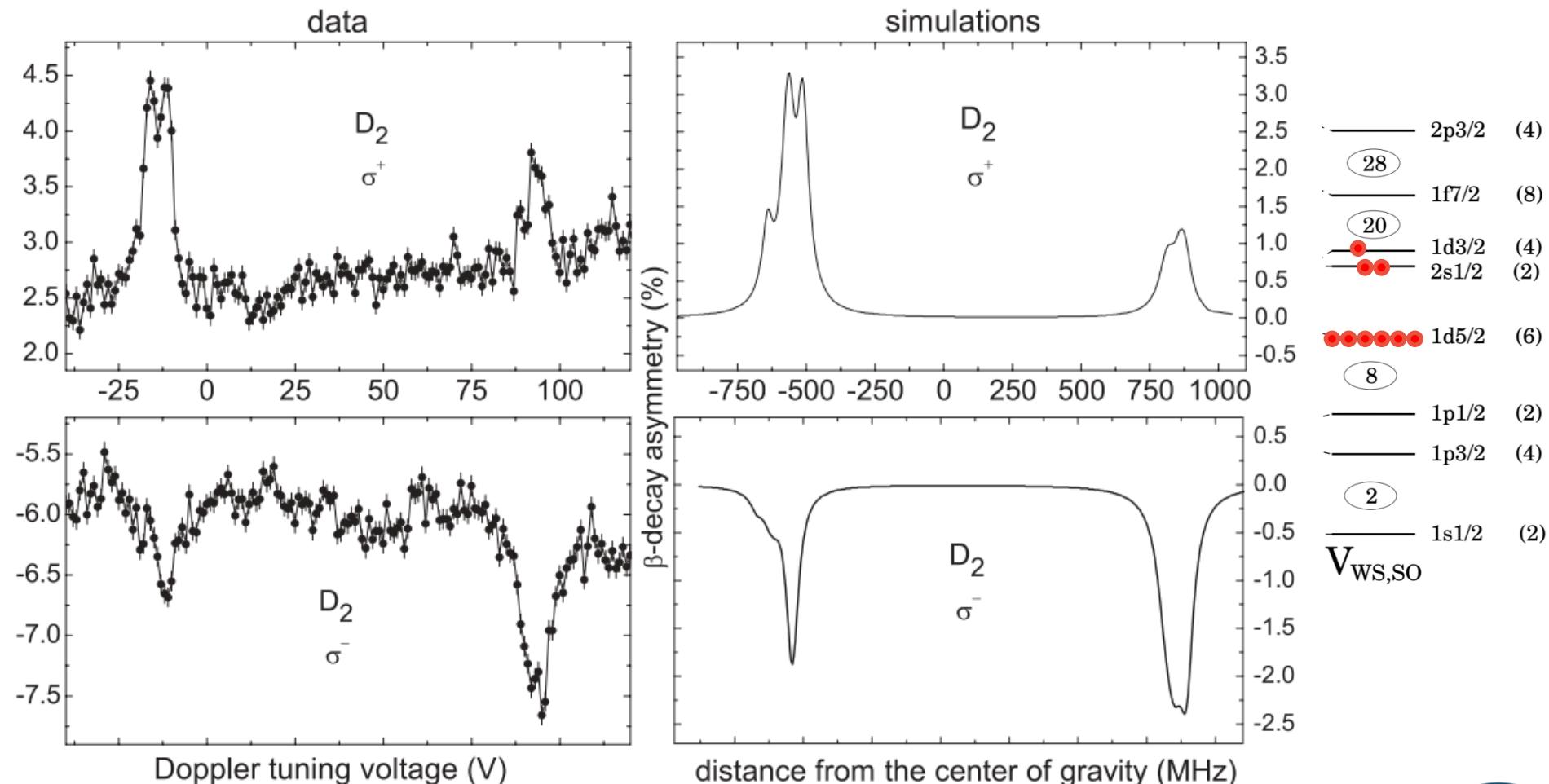
$$\mu_I > 0$$



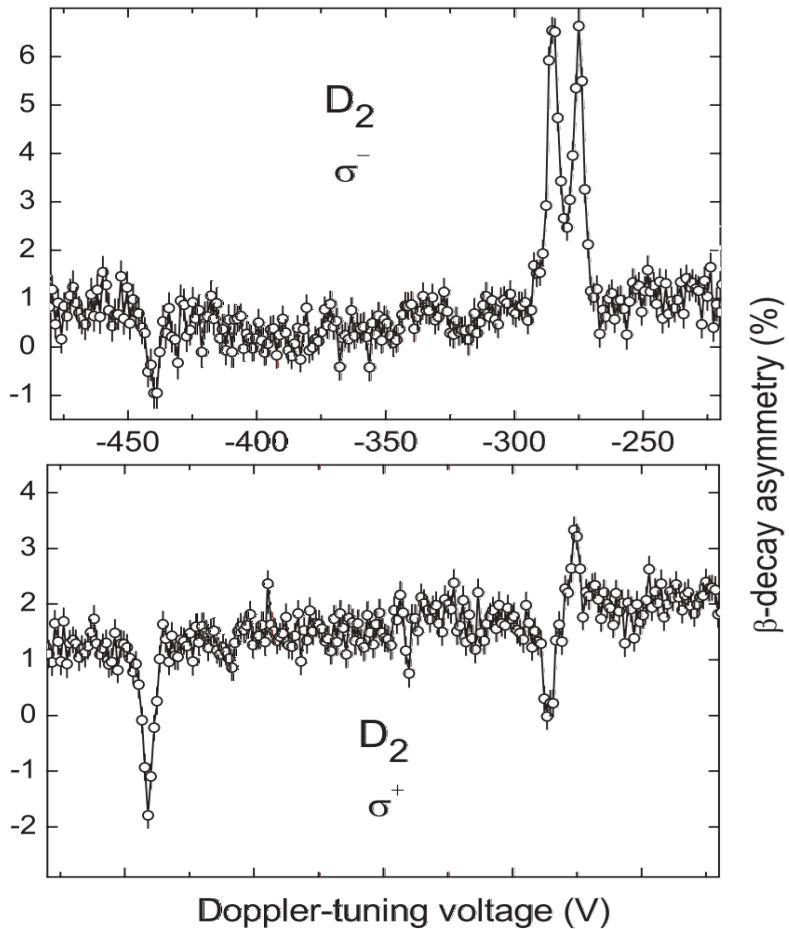
$2p\ 3/2$	(4)
$1f\ 7/2$	(8)
$2s\ 1/2$	(2)
$1d\ 5/2$	(6)
$1p\ 1/2$	(2)
$1p\ 3/2$	(4)
$1s\ 1/2$	(2)
$V_{WS,SO}$	



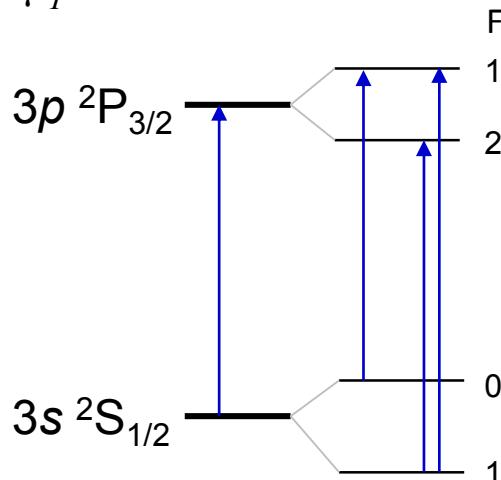
# $\beta$ -Asymmetry Detection of $^{29}\text{Mg}$



# $\beta$ -Asymmetry Detection of $^{31}\text{Mg}$



$I = 1/2 ??$   
 $\mu_I < 0$



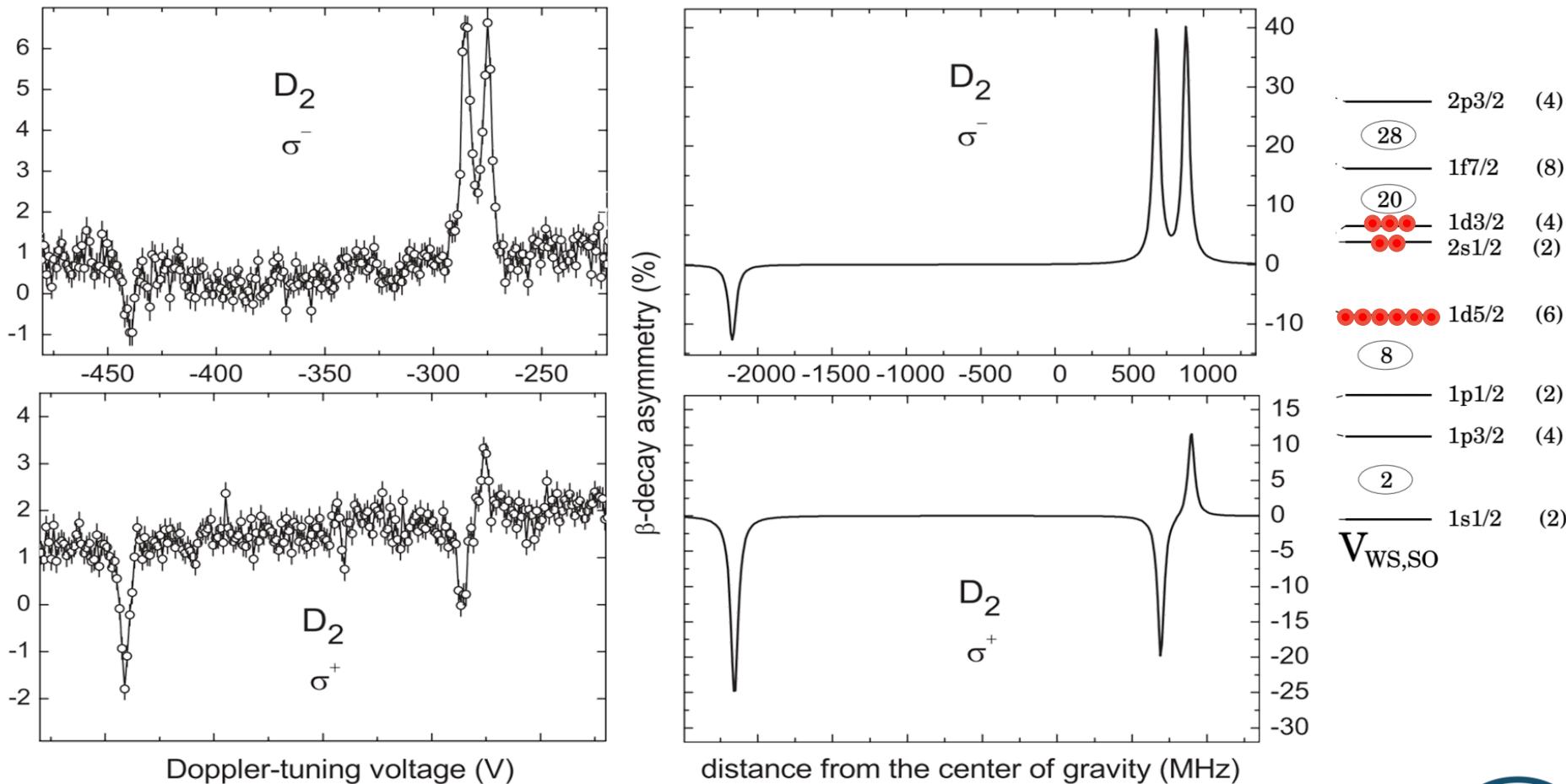
$2\text{p}\ 3/2$	(4)
(28)	
$1\text{f}\ 7/2$	(8)
(20)	
$1\text{d}\ 3/2$	(4)
$2\text{s}\ 1/2$	(2)
(6)	
$1\text{d}\ 5/2$	(6)
(8)	
$1\text{p}\ 1/2$	(2)
$1\text{p}\ 3/2$	(4)
(2)	
$1\text{s}\ 1/2$	(2)
$V_{\text{WS},\text{SO}}$	



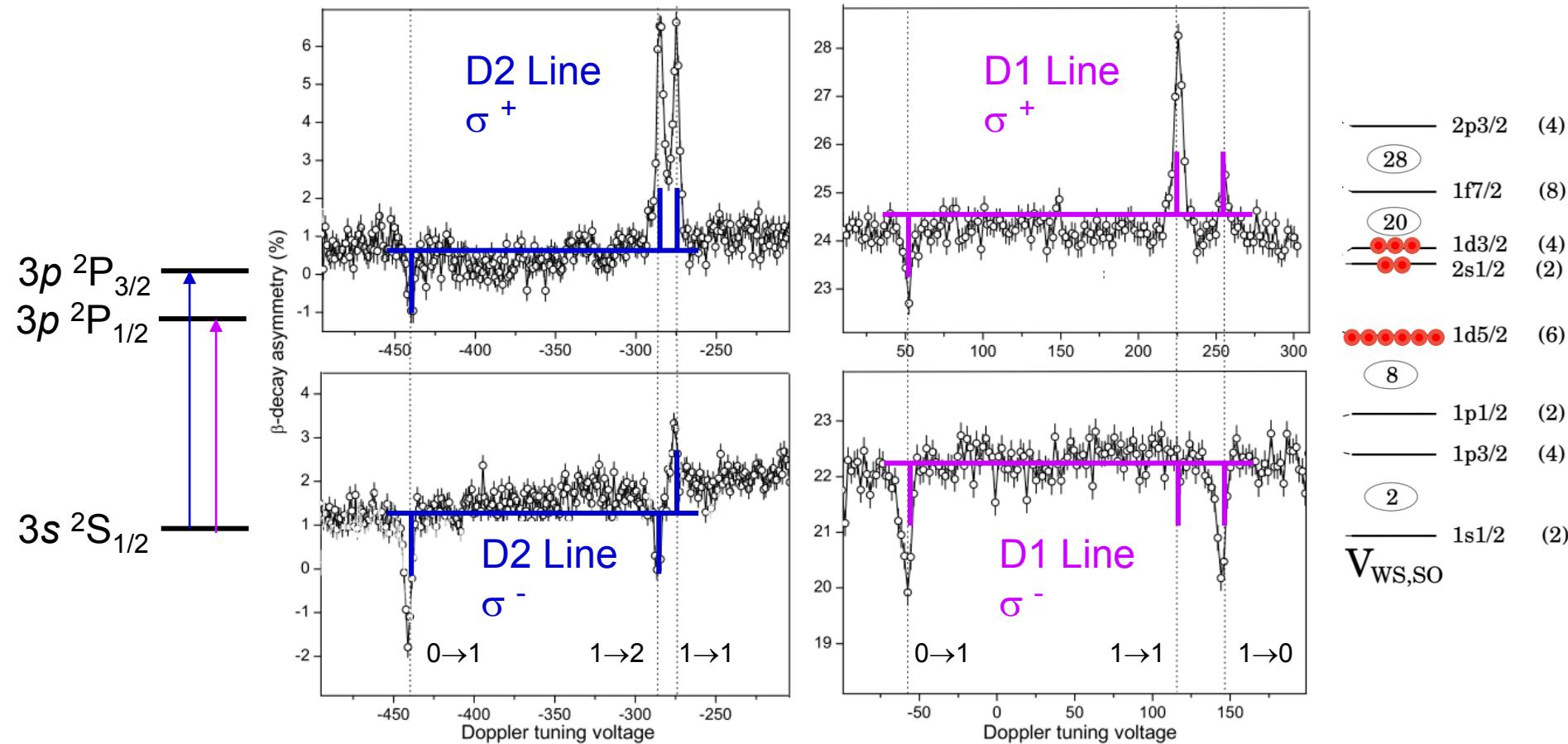
# $\beta$ -Asymmetry Detection of $^{31}\text{Mg}$



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# $\beta$ -Asymmetry Detection of $^{31}\text{Mg}$



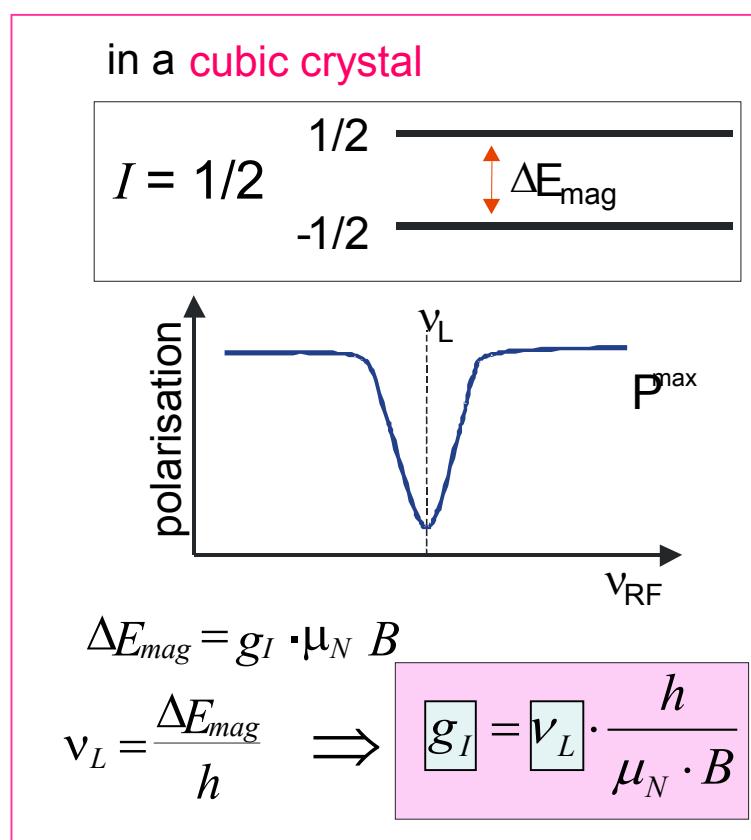
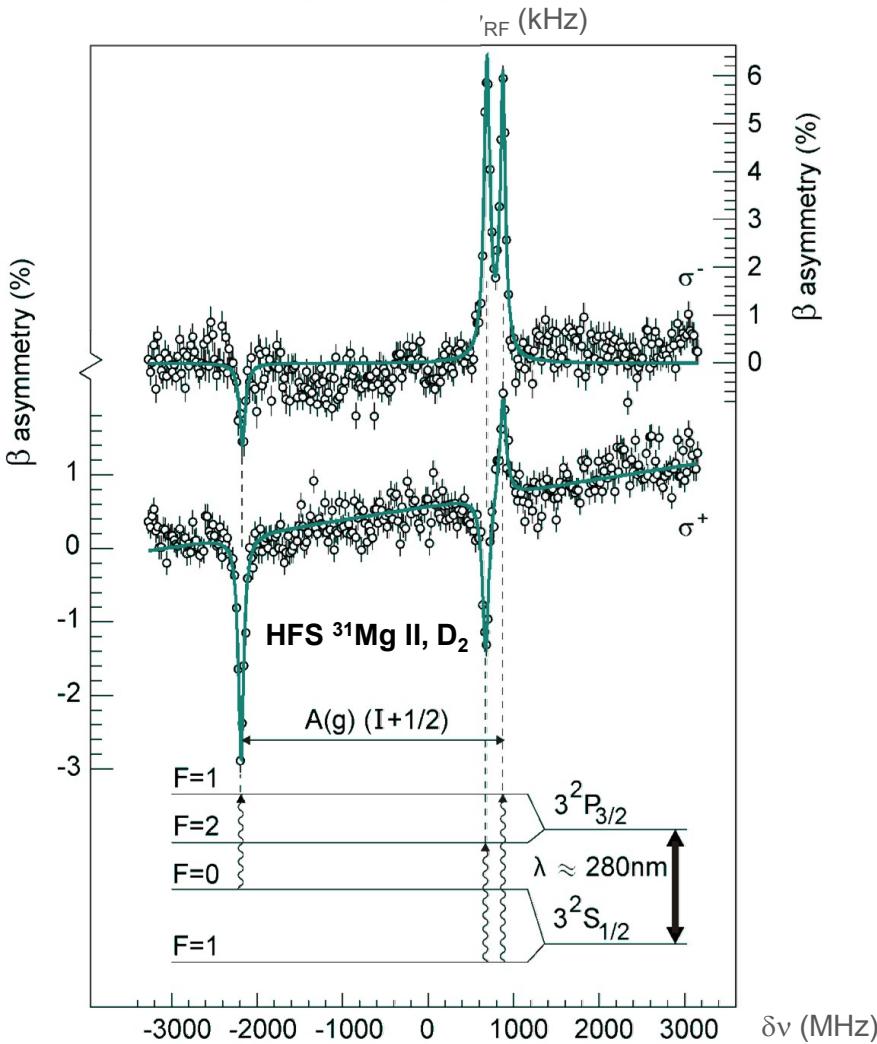
Eur. Phys. J. A **25**, s01, 193–197 (2005)



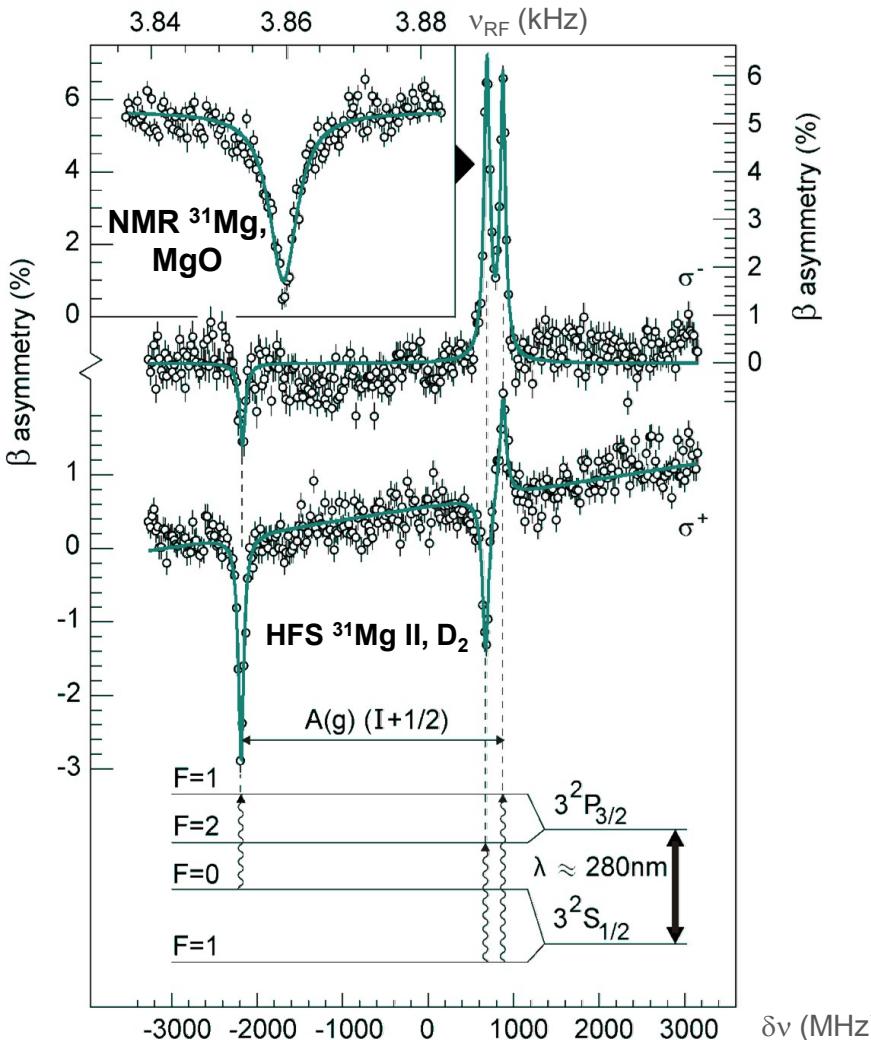
Nuclear Spin :  $I = 1/2$   
Expected:  $I = 3/2$



# $\beta$ -Nuclear Magnetic Resonance in $^{31}\text{Mg}$



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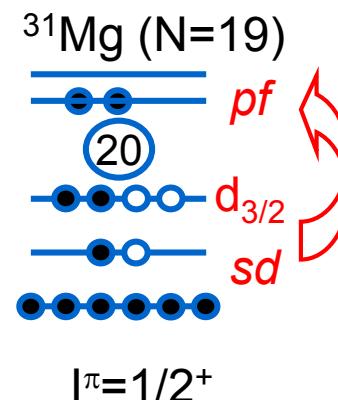
$$\Delta E_{\text{HFS}} = |A| \left( I + \frac{1}{2} \right)$$

$A/g = \text{const along chain}$

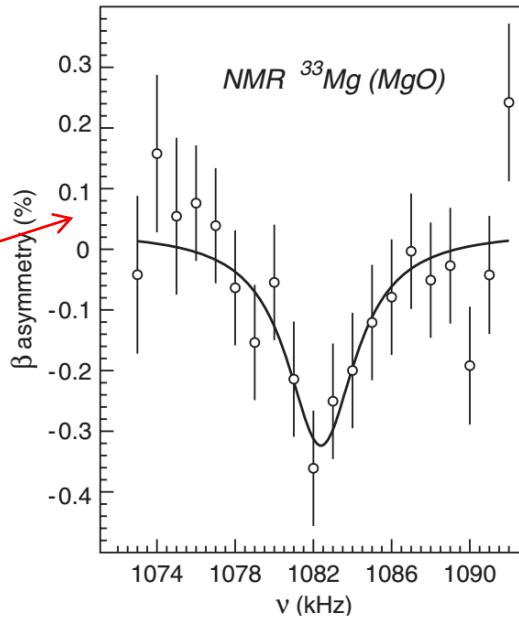
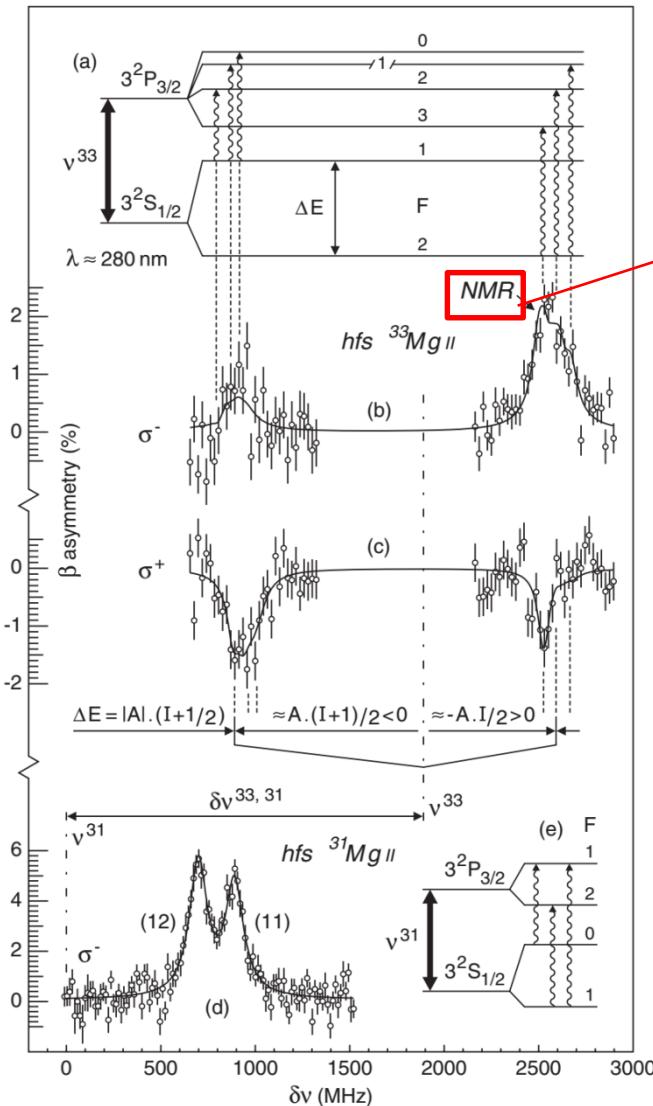
$|g|$  from NMR

$\rightarrow I$

Proportionality factor  $A/g$  are known from stable isotopes



# $\beta$ -Nuclear Magnetic Resonance in $^{31}\text{Mg}$



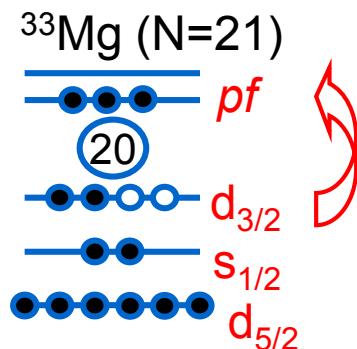
$n(\hbar\omega)$	$I^\pi$	WBMB			SD-PF		
		$Q$ (mb)	$E$ (keV)	$g_{\text{free}}$	$Q$ (mb)	$E$ (keV)	$g_{\text{free}}$
0	$3/2^-$	-1.47	-83	737	-1.35	-91	2374
1	$3/2^+$	0.75	135	399	0.78	140	283 <sup>c</sup>
2	$3/2^-$	-0.45 <sup>a</sup>	147 <sup>b</sup>	1065	-0.47 <sup>a</sup>	157 <sup>b</sup>	0 <sup>c</sup>

<sup>a</sup>Experimental gyromagnetic ratio from this work  $g = -0.4971(4)$ .

<sup>b</sup> $Q(\beta_C) = 151(38)$  mb, calculated from  $\beta_C$  [12].

<sup>c</sup>The  $3/2^+$  ( $1\hbar\omega$ ) and  $3/2^-$  ( $2\hbar\omega$ ) states are inverted in respect to the calculations presented in Ref. [11].

$$\begin{aligned}\Delta E_{\text{HFS}} &= |A| \left( I + \frac{1}{2} \right) \\ \Delta E_{\text{HFS}} &= 1744.2(7) \text{ MHz} \\ A/g &= \text{const along chain} \\ |g| &= 0.4971 \text{ (NMR)} \\ \rightarrow A_g &= 866.2(7) \text{ MHz} \\ \rightarrow I &= \frac{3}{2}\end{aligned}$$



$$I^\pi = 3/2^-$$



# Keep in Mind



- Optical hyperfine structure measurements can reveal magnetic moments (**size and sign**)!
- The magnetic moment is very sensitive to the wavefunction composition of a nuclear state
- $\beta$ -Asymmetry detection after optical pumping is a sensitve tool to detect atomic resonance transitions
- $\beta$ -NMR can provide accurate values of nuclear g-factors
- Measuring the nuclear g factor and the hyperfine splitting provides a direct measurement of the nuclear spin  $I$

