Off-line and On-line Applications of High Resolution Laser Spectroscopy on Exotic Species

Collinear and Alternative Approaches

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Outline

• The Study of Exotic Nuclides – from the Periodic Table to the Nuclear Chart

• Scientific Findings and Data from laser spectroscopy
  – experimental prerequisites and techniques
  – high resolution laser spectroscopy
  – line broadenings
  – collinear versus other experimental techniques

• Some Specific Results on most Exotic Elements and Isotopes

• Summary and Outlook
The Periodic System 2019 – with todays Exotic Elements

Definition of Exotic Elements: abundance in the geosphere $<< 10^{-9}$ ppm (10$^{-15}$)

$^{43}$Tc, $^{61}$Pm, $^{85}$At, $^{87}$Fr, Acti- & Transactinides

...going on-line – heading for exotic isotopes far off stability...
High resolution laser spectroscopy on exotic nuclides gives access to the majority of nuclear ground state properties, i.e.

- nuclear spin \( I \)
- magnetic dipole moment \( \mu_I \) (= single particle property)
- electric quadrupole moment \( Q_s \) (= collective deformation)
- nuclear charge radius \( \delta \langle r^2 \rangle \) (including deformation \( \beta \))

→ Prerequisite is the understanding of the atomic physics

The nuclear chart is tracking the pathway from the Big Bang to the world around us...

... or from **Exotic Elements** to **Exotic Nuclides**...
The Influence of the Nucleus on the Atomic Structure

\[ H\Psi = E\Psi \]

\[ \sum_{i=1}^{N} -\frac{\hbar^2}{2m} \nabla^2 \]

\[ U + V \rightarrow V(\bar{r}_1 \bar{s}_1, \bar{r}_2 \bar{s}_2 \ldots \bar{r}_n \bar{s}_n) \]

\[ \frac{\bar{P}^2}{2\mu} = \sum \frac{\bar{P}_i^2}{2\mu} + \sum \sum_{i>j} \frac{\bar{P}_i \cdot \bar{P}_j}{\mu} \]

Normal Mass Shift

Specific Mass Shift

Field Shift

Hyperfine Structure

\[ \Delta \nu_{yr} = \nu_y^0 \frac{m_e}{m_p} \frac{A - A'}{A A'} \]

\[ + \frac{C_y \nu_y^0}{Z} \frac{(A - A')}{A A'} \]

\[ + \frac{\pi a_0^3}{\lambda} \frac{\Delta \psi(0)^2}{f(z)} \left[ \delta(r^2) A^4 \right] + C \delta(r^4) A^4 + \ldots \]

\[ \Delta \nu_{IS} = (M_N + M_S) \frac{(A - A')}{A A'} \left[ F \delta(r^2) A^4 \right] \]

\[ \rightarrow \text{Mean squared nuclear charge radius difference and deformation } \beta \]
From Hyperfine Structure to the Nuclear Moments $\mu_I$ and $Q_s$

Atomic Level Splittings by Coupling of Electron Angular Momentum $J$ and Nuclear Spin $I$ via the Moments $\mu_I$ and $Q_s$

$$W_D = -\mu \cdot B$$

$$W_Q = eQ_s (\partial^2 V / \partial z^2)$$

$$\vec{F} = \vec{I} + \vec{J} \quad (|I - J| \leq F \leq I + J)$$

Nuclear Magnetic Dipole Moment $\mu_I$

$$A = \mu_I B_e(0) / (IJ)$$

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

Nuclear Electric Quadrupole Moment $Q_s$

$$W_F = \frac{1}{2} AC + B \left( \frac{3}{4} C(C + 1) - I(I + 1)J(J + 1) \right) \frac{2I(2I - 1)J(2J - 1)}{2I(2I - 1)J(2J - 1)}$$

$$C = F(F + 1) - I(I + 1) - J(J + 1).$$
Resolution in laser spectroscopy determined by

- Single free atom at rest → natural linewidth = Lorentzian of ~10 MHz
- Ensemble of thermally moving atoms in vapor → Gaussian 500 MHz – 5 GHz
- Additional contribution from laser line width → Gaussian 1 MHz (cw) – 5 GHz (pulsed)
- Strong linewidth suppression down to natural linewidth by fast beam Doppler compression in collinear laser spectroscopy (on ions, atoms or molecules)

Lorentzian (homogeneous)

\[ L(v) = \frac{1}{\pi [w_L + (v_0 - v)^2 / w_L]} \]
\[ w_L = HWHM = \frac{1}{4\pi} \]

Gaussian (inhomogeneous)

\[ G(v) = \frac{1}{w_G \sqrt{\pi}} \exp\left[-(v_0 - v)^2 / w_G^2\right] \]
\[ w_G = HWHM = 4.3 \times 10^7 v_0 \sqrt{T / M} \]

Voigt (convolution)

\[ V(v) = \int_{-\infty}^{\infty} G(v')L(v-v') dv' \]
Principles of Collinear Laser Spectroscopy

Radioactive Ion Beam Production and Purification

\[ \nu_{\text{Ion}} = \nu_{\text{Laser}} \cdot \gamma \cdot \left( 1 - \frac{\nu}{c} \right) \]

\[ E = eU = \frac{1}{2} m \nu^2 \]
\[ \delta E = m \nu \delta \nu \]
The Cradle of Collinear Laserspectroscopy...

at the MAFIA on-line separator of the TRIGA Research Reactor of UMz in 1978

AN ON-LINE MASS SEPARATOR FOR FISSION-PRODUCED ALKALI ISOTOPES

Institut für Physik, Johannes Gutenberg-Universität, D-6500 Mainz, Federal Republic of Germany

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


Short Note

Hyperfine Structure and Isotope Shifts of Neutron-Rich $^{138-142}$Cs

J. Bonn, W. Klempt, R. Neugart, E.-W. Otten, and B. Schinzler
Institut für Physik, Johannes Gutenberg Universität, Jakob-Welder-Weg
Mainz
Federal Republic of Germany

COLLINEAR LASER SPECTROSCOPY OF NEUTRON-RICH Cs ISOTOPES AT AN ON-LINE MASS SEPARATOR

B. SCHINZLER, W. KLEMP, S.L. KAUFMAN, H. LOCHMANN,
G. MORUZZI 2, R. NEUGART, E.-W. OTTEN, J. BONN,
L. VON REISKY, K.P.C. SPATH, J. STEINACHER and D. WESKOTT
Institut für Physik, Universität Mainz, Germany

20 November 1978
The first Hyperfine Structure Spectra in Radiocesium

In reactor core ion source limited to alkaline elements  
→ Transfer of CLS to ISOLDE CERN in 1980
The Prosperous First 10 Years of CLS at ISOLDE/CERN

1982

0. Fast-Beam Laser Spectroscopy on Metastable Atoms applied to Neutron-Deficient Ytterbium Isotopes
   F. Buchinger, A.C. Mueller, B. Schinzler, K. Wendt,
   C. Ekström, W. Klempt, and R. Neugart,
   Nuclear Instruments and Methods 202, 159-165 (1982)

1983

1. Spins, Moments and Charge Radii of Barium Isotopes in the Range of $^{122-146}$Ba determined by Collinear Fast-Beam Laser Spectroscopy
   A.C. Mueller, F. Buchinger, W. Klempt and E.W. Otten, R. Neugart, C. Ekström,
   J. Heinemeier and The ISOLDE Collaboration,
   Nuclear Physics A403 (1983) 234-262

2. Nuclear Moments and Charge Radii of Rare-Earth Isotopes studied by Collinear Fast-Beam Laser Spectroscopy
   R. Neugart, K. Wendt, S.A. Ahmad, W. Klempt, and C. Ekström,
   Hyperfine Interactions 15/16, 181-186 (1983)

3. Determination of Nuclear Spins and Moments in a Series of Radium Isotopes
   S.A. Ahmad, W. Klempt, R. Neugart, E.W. Otten, K. Wendt, and C. Ekström,

1984

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This image includes references to various spectroscopic studies conducted in the 1980s, particularly focusing on laser spectroscopy and its applications to atomic and nuclear physics. The studies cover a range of elements, including Ytterbium, Barium, Rare-Earth Isotopes, and Radium, showcasing the advancements in spectroscopic techniques during this period.
Nuclear Structure from on-line High Res Laser Spectroscopy

Data on 38 isotopic chains from resonant interaction between laser light and atoms

Verification of a nuclear sub-shell closure at Z = 64

Evidence for tri-axially shaped deformed nuclei

Charge radii of Halo nuclei

One-atom-at-a-time spectroscopy towards superheavy species

Detection of nuclear octupole deformation

Proof of isomerism by shape coexistence

Primary prerequisites for reaching exotic isotopes
- Isobarically pure production of exotic isotopes e.g. by RILIS
- High sensitivity studies down to lowest yield isotopes
- Leading position of ISOLDE but also other facilities contribute
- Knowledge of atomic spectra of all (also exotic) elements

Life times of r-process waiting point nuclei

ISOLDE Experimental Hall with Laser & Mass Spectrometry

3. RILIS – Resonance Ionization Laser Ion Source & Mid to High Resolution In-Source Spectroscopy

4. GANDALF – Collinear Negative Ion Photo-Detachment

1. COLLAPS – Collinear Laser Spectroscopy

2. CRIS – Collinear Laser Resonance Ionization

5. VITO – Laser Ion Beam Polarization

To NICOLE

To ISOLTRAP – Precision Mass Spectrometry
Nuclear Polarization and $\beta$-NMR Detection in CLS

Cubic LiF crystal $I = \frac{3}{2}$
$\mu_i = 3.6673$ n.m.

NUCLEAR SPIN AND MAGNETIC MOMENT OF $^{11}$Li
Upgrading of Collaps by Ion Beam Pulsing

HFS Studies in $^{208}$Bi

Resonance Ionization Detection in CLS

Ion Bunch from ISOLDE
Charge Exchange Cell

Decay Spectroscopy Station & Ion Detection

Interaction region (ultra high vacuum to minimize collisional ionization)

Versatile combination with different nuclear $\alpha$, $\beta$, $\gamma$ detectors possible
The CRIS Collaboration

Recent CRIS on-line Experiments

**Indium:**
- Laser spectroscopy up to $^{101}$In ($Z=49, N=52$)
- Yields ~ 100 ions/s

**Potassium:**
- Laser spectroscopy of $^{52}$K ($Z=19, N=33$)

**Tin:**
- Laser spectroscopy of $^{103-122}$Sn

First on-line Spectroscopy on molecules
- RaFluoride

Excitation energy of low-lying levels of $^{226}$RaF
The Need of a full Collection of Lasers

Pulsed
- Ti:sal Z cavity
- LEE
- Brilliant
- Ti:sal Z cavity
- PDL
- Brilliant
- Inj.-locked
- Litron
- Inj.-locked
- Litron
- Inj.-locked
- COBRA
- Litron
- SHG
- WS6
- THG

CW
- DL PROC
- HeNe
- WSU2
- Millenia
- Matisse
- SHG
- Sprout
- MSquared
- SHG

Figure by Agi Koszorus, CERN and KUL
• Resolution limited by **Doppler broadening** in the hot ion source and lasers (FWHM ≈ 15 GHz)
• **In-RILIS Spectroscopy** for heavy elements with large isotope shift & hyperfine structure
• Direct in-source laser spectroscopy on hyperfine structure & isotope shift of $^{196,199,205,212,217}$At

![Diagram showing energy levels and transitions for various isotopes of At.](image)
Suppression of Contaminations in In-Source Spectroscopy
**Nuclear Ground State Properties of At from In-RILIS Spec**

### Table I. Measured values of the hyperfine structure and isotope shift of full sequence of $^{195-211}$At isotopes.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$N$</th>
<th>$I^\pi$</th>
<th>$\delta(r^2)_{A,205}$ (fm$^2$)</th>
<th>$\beta_{DM}$</th>
<th>$\mu_\bullet (\mu_B)$</th>
<th>$Q_S$ (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{195}$At$^g$</td>
<td>110</td>
<td>(1/2$^+$)</td>
<td>-0.171(7)[9]</td>
<td>0.21(2)</td>
<td>1.161(25)[39]</td>
<td>-2.04(25)[100]</td>
</tr>
<tr>
<td>$^{195}$At$^m$</td>
<td>110</td>
<td>(7/2$^+$)</td>
<td>-0.101(7)[5]</td>
<td>0.22(2)</td>
<td>3.714(97)[90]</td>
<td>-0.64(13)[35]</td>
</tr>
<tr>
<td>$^{196}$At$^g$</td>
<td>111</td>
<td>(3$^+$)</td>
<td>-0.262(10)[13]</td>
<td>0.17(2)</td>
<td>3.739(110)[90]</td>
<td>-1.15(8)[60]</td>
</tr>
<tr>
<td>$^{196}$At$^m$</td>
<td>112</td>
<td>(9/2$^+$)</td>
<td>-0.296(7)[15]</td>
<td>0.15(3)</td>
<td>3.849(45)[54]</td>
<td>-1.15(8)[60]</td>
</tr>
<tr>
<td>$^{197}$At$^g$</td>
<td>112</td>
<td>(9/2$^+$)</td>
<td>-0.133(7)[7]</td>
<td>0.19(2)</td>
<td>1.546(13)[37]</td>
<td>-0.59(15)[30]</td>
</tr>
<tr>
<td>$^{197}$At$^m$</td>
<td>112</td>
<td>(3$^+$)</td>
<td>-0.338(7)[17]</td>
<td>0.11(4)</td>
<td>4.037(94)[97]</td>
<td>-0.59(15)[30]</td>
</tr>
<tr>
<td>$^{198}$At$^g$</td>
<td>113</td>
<td>(3$^+$)</td>
<td>-0.315(7)[16]</td>
<td>0.12(3)</td>
<td>2.554(81)[62]</td>
<td>-0.44(25)[25]</td>
</tr>
<tr>
<td>$^{198}$At$^m$</td>
<td>113</td>
<td>(3$^+$)</td>
<td>0.265(7)[13]</td>
<td>0.12(3)</td>
<td>3.955(45)[56]</td>
<td>-0.95(8)[50]</td>
</tr>
<tr>
<td>$^{200}$At$^g$</td>
<td>114</td>
<td>(9/2$^+$)</td>
<td>0.075(10)[4]</td>
<td>0.17(2)</td>
<td>1.595(38)[39]</td>
<td>-0.50(8)[50]</td>
</tr>
<tr>
<td>$^{200}$At$^m$</td>
<td>114</td>
<td>(9/2$^+$)</td>
<td>-0.293(7)[15]</td>
<td>0.08(4)</td>
<td>4.279(96)[110]</td>
<td>-0.96(12)[50]</td>
</tr>
<tr>
<td>$^{200}$At$^g$</td>
<td>115</td>
<td>(3$^+$)</td>
<td>-0.277(7)[14]</td>
<td>0.09(5)</td>
<td>4.74(13)[12]</td>
<td>-0.96(12)[50]</td>
</tr>
<tr>
<td>$^{200}$At$^m$</td>
<td>115</td>
<td>(7$^+$)</td>
<td>-0.258(9)[13]</td>
<td>0.10(4)</td>
<td>2.694(62)[65]</td>
<td>-0.54(25)[30]</td>
</tr>
<tr>
<td>$^{202}$At$^g$</td>
<td>116</td>
<td>(7$^+$)</td>
<td>-0.197(7)[10]</td>
<td>0.04(9)</td>
<td>4.16(12)[10]</td>
<td>-0.65(13)[30]</td>
</tr>
<tr>
<td>$^{202}$At$^m$</td>
<td>116</td>
<td>(7$^+$)</td>
<td>0.201(10)[10]</td>
<td>0.06(6)</td>
<td>4.54(16)[11]</td>
<td>-0.73(8)[35]</td>
</tr>
<tr>
<td>$^{203}$At$^g$</td>
<td>118</td>
<td>9/2$^-$</td>
<td>-0.115(7)[6]</td>
<td>0.08(5)</td>
<td>4.02(15)[57]</td>
<td>-0.62(8)[30]</td>
</tr>
<tr>
<td>$^{203}$At$^m$</td>
<td>119</td>
<td>7$^-$</td>
<td>0.109(7)[5]</td>
<td>0.08(5)</td>
<td>4.84(13)[12]</td>
<td>-0.62(8)[30]</td>
</tr>
<tr>
<td>$^{204}$At$^g$</td>
<td>120</td>
<td>9/2$^-$</td>
<td>0</td>
<td>0.08(4)</td>
<td>4.11(13)[58]</td>
<td>-0.61(8)[30]</td>
</tr>
<tr>
<td>$^{204}$At$^m$</td>
<td>121</td>
<td>9/2$^-$</td>
<td>0.020(7)[1]</td>
<td>0.06(6)</td>
<td>4.39(13)[11]</td>
<td>-0.42(10)[20]</td>
</tr>
<tr>
<td>$^{206}$At$^g$</td>
<td>122</td>
<td>9/2$^-$</td>
<td>0.115(7)[6]</td>
<td>0.08(4)</td>
<td>4.15(45)[59]</td>
<td>-0.42(10)[20]</td>
</tr>
<tr>
<td>$^{206}$At$^m$</td>
<td>123</td>
<td>6$^+$</td>
<td>0.155(7)[8]</td>
<td>0.08(4)</td>
<td>4.48(14)[11]</td>
<td>-0.42(10)[20]</td>
</tr>
<tr>
<td>$^{207}$At$^g$</td>
<td>124</td>
<td>9/2$^-$</td>
<td>0.240(7)[12]</td>
<td>0.09(3)</td>
<td>4.14(45)[59]</td>
<td>-0.42(10)[20]</td>
</tr>
<tr>
<td>$^{207}$At$^m$</td>
<td>125</td>
<td>5$^+$</td>
<td>0.295(7)[15]</td>
<td>0.09(3)</td>
<td>4.74(12)[11]</td>
<td>-0.42(10)[20]</td>
</tr>
<tr>
<td>$^{208}$At$^g$</td>
<td>126</td>
<td>9/2$^-$</td>
<td>0.372(9)[19]</td>
<td>0.09(2)</td>
<td>4.13(37)[b]</td>
<td>-0.33(12)[20]</td>
</tr>
<tr>
<td>$^{208}$At$^m$</td>
<td>126</td>
<td>9/2$^-$</td>
<td>0.372(9)[19]</td>
<td>0.09(2)</td>
<td>4.13(37)[b]</td>
<td>-0.33(12)[20]</td>
</tr>
</tbody>
</table>

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**Footnotes:**

- For $I = 5$, $\delta(r^2)_{A,205} = 0.009(7)[1] \text{ fm}^2$, $\mu = 4.34(12)[11] \mu_B$, $Q_S = -0.29(10)[15]$. Spin assignment for $^{206}\text{At}$ is discussed in Sec. V A 3.
- Reference value.
- Frequency detuning $\nu - \nu_{211}^0$ (GHz).
Charge Radii and Deformations in Astatine

- Ground state & isomer nuclear charge radii – almost a renaissance of the Hg shape staggering?
- Decrease in odd-even staggering points to onset of octupolar deformed nuclei around \( N = 145 \)

\[ \delta(R_{1211}) \text{ (fm)} \]

\[ \beta_{OM} = 0.25 \]
\[ \beta_{OM} = 0.20 \]
\[ \beta_{OM} = 0.15 \]
\[ \beta_{OM} = 0.10 \]
\[ \beta_{OM} = 0.00 \]

\[ N \]
\[ 110 \]
\[ 112 \]
\[ 114 \]
\[ 116 \]
\[ 118 \]
\[ 120 \]
\[ 122 \]
\[ 124 \]
\[ 126 \]

\[ A \]
\[ 195 \]
\[ 197 \]
\[ 199 \]
\[ 201 \]
\[ 203 \]
\[ 205 \]
\[ 207 \]
\[ 209 \]
\[ 211 \]

\[ R \text{ (fm)} \]
\[ 5.2 \]
\[ 5.3 \]
\[ 5.4 \]
\[ 5.5 \]
\[ 5.6 \]
\[ 5.7 \]
\[ 5.8 \]

Next Generation – High-Resolution In-RILIS/LIST Spec.

LASER ION SOURCE TRAP
with Cross-Beam Geometry
prevents Doppler Broadening

Standard RILIS Hot Cavity Ionizer

Standard Ti:Sa for Ionization
Linewidth: 5-10 GHz

Pulsed Narrowband Spectroscopy Laser System
Linewidth: 20 MHz

Injection-locked Ti:Sa Laser
EC Diode Laser

PC – Control & Stabilization

Ultimate Background Suppression by Double Repeller LIST Design

„Background-free“ mass spectrum

RILIS

99Tc

Electron Impact Background

LIST

99Tc

Suppression of any positive or negative charged species

π-LIST efficiency estimated to 0.1 - 1 %
High Resolution In-LIST Spectroscopy

HFS and IS of $^{97-99}$Tc

measured off-line at the RISIKO RIB facility at JGU Mz on samples $< 10^{11}$ atoms in the $\pi$-LIST

Lowest background $< 1$ cps

Experimental linewidth $\sim 50$ MHz
Off-line High-Resolution Laser Spec on Pm

Sample specs from γ spectroscopy

Ratio Pm/Nd ≈ 1/100 after radiochemistry

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Handling limit (kBq)</th>
<th>A total (kBq)</th>
<th>total atom number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pm-143</td>
<td>1000</td>
<td>56</td>
<td>2.04e12</td>
</tr>
<tr>
<td>Pm-144</td>
<td>1000</td>
<td>85</td>
<td>3.83e12</td>
</tr>
<tr>
<td>Pm-145</td>
<td>10000</td>
<td>? (no γ)</td>
<td>?</td>
</tr>
<tr>
<td>Pm-146</td>
<td>1000</td>
<td>8.5</td>
<td>1.87e12</td>
</tr>
<tr>
<td>Pm-147</td>
<td>10000</td>
<td>? (no γ)</td>
<td>?</td>
</tr>
<tr>
<td>Pm-148m</td>
<td>1000</td>
<td>21</td>
<td>1.25e12</td>
</tr>
</tbody>
</table>

The Nuclear Chart

Cutout of the Lanthanides

18 MeV protons @ UH Bern

High Resolution In-Source Laser Spectroscopy

PI-LIST ion source

Repeller electrodes

Atomizer

Pm sample

45 mm

Quadrupole rods

Hot Cavity

30 kV Extraction

Sample Reservoir

Deflectors

Einzellens

Quadrupole Lens

Dipole Magnet

Separator Slit

Faraday Cup

Laser Beams

Al 45120.8 cm\(^{-1}\)

849 nm

J = 7/2

S.E.S

33352.2 cm\(^{-1}\)

887 nm

F.E.S

22080.0 cm\(^{-1}\)

452 nm

G.S.

0 cm\(^{-1}\)

4f\(^5\)6s\(^2\) 6H\(^{5/2}\)

Al 45128.2 cm\(^{-1}\)

804 nm

J = 7/2

G.S.

468 nm

45021 cm\(^{-1}\)

45008.9 cm\(^{-1}\)

422 nm

45128.2 cm\(^{-1}\)

32683.5 cm\(^{-1}\)

882 nm

33352.2 cm\(^{-1}\)

21348.1 cm\(^{-1}\)

22080.0 cm\(^{-1}\)

4f\(^5\)6s\(^2\) 6H\(^{5/2}\)
HFS spectra of $^{143-147}$Pm

- exp. linewidth FWHM $\sim$100 MHz
- extracted A and B parameters agree for 452 nm and 468 nm transition
Nuclear Charge Radii in Pm

- Electronic factor ratio from King-Plot
- **SMS** neglected, $F$ interpolated from neighboring elements
- Indication of small odd-even staggering

Reference Data:
I. Angeli, K.P. Marinova / Atomic Data and Nuclear Data Tables 99 (2013) 69–95
Conclusion and Outlook

- **High resolution laser spectroscopy** delivers most valuable *nuclear ground state properties* as well as *atomic physics information* within long isotopic chains up to the most exotic, short-lived isotopes
  - Experimental resolution in the order of natural atomic line widths needed

- Collinear Laser Spectroscopy still is the most versatile technique

- Various sensitive detection techniques are in use
  - **Standard fluorescence detection** still very prosperous after 40 years of use
  - **Nuclear polarization** and *β-NMR detection*
  - **Resonance ionization** enables efficient detection of ions or nuclear decays
  - **Cooler and buncher** combinations for background reduction
  - On-line Collinear **Photodetachment Spectroscopy** for study on exotic negative ions

- **Alternative techniques** found in high resolution *in-source* spectroscopy
Acknowledgements

Thank you for your attention – and these gentlemen and their actual colleagues for their work
Ultra Trace Analysis by Collinear Fast Beam Laser Spectroscopy

$^{89,90}$Sr Ultra Trace Analysis by RIMS

- **Isotopic Selectivity:** $\geq 10^{10}$
  - (background limited)
- **Overall Efficiency:** $\sim 10^{-5}$
  - (laserpower limited)
- **Detection Limit:** $\sim 3 \times 10^6$ atoms $^{90}$Sr per sample ($\sim 2$ mBq)

**30 keV Ion-Source + Acceleration**

**Fixed Frequency Laser**

**Magnetic Sectorfield Mass-Separator**

**Neutralization**

**Quasi-collinear Selective Optical Excitation**

**State Selective Field-Ionization**

**Energy Filter**

**Detection**

**1-Step Quasi-collinear RIS**

- $5s\,4d\,^{3}D_{J} \rightarrow 5s\,23f\,^{3}F_{J}$
  - (363.8 nm)
- + 17 keV field ionization
Isotope Selection by Collinear Fast Beam Laser Spectroscopy

Fast atomic beam (energy 50 keV):
Selectivity > $10^9$ per excitation step

No isotope resolution - no selectivity