Лазерно-спектроскопические исследования изотопов таллия.

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1. Общий обзор результатов
   по исследованию изотопов таллия.
2. Экспериментальная установка.
3. Что такое «аномалия сверхтонкой структуры» и новый метод ее измерения.
4. Экспериментальные результаты: HFA для изомеров таллия с I=9/2. Какую информацию о ядре можно получить из данных по HFA?

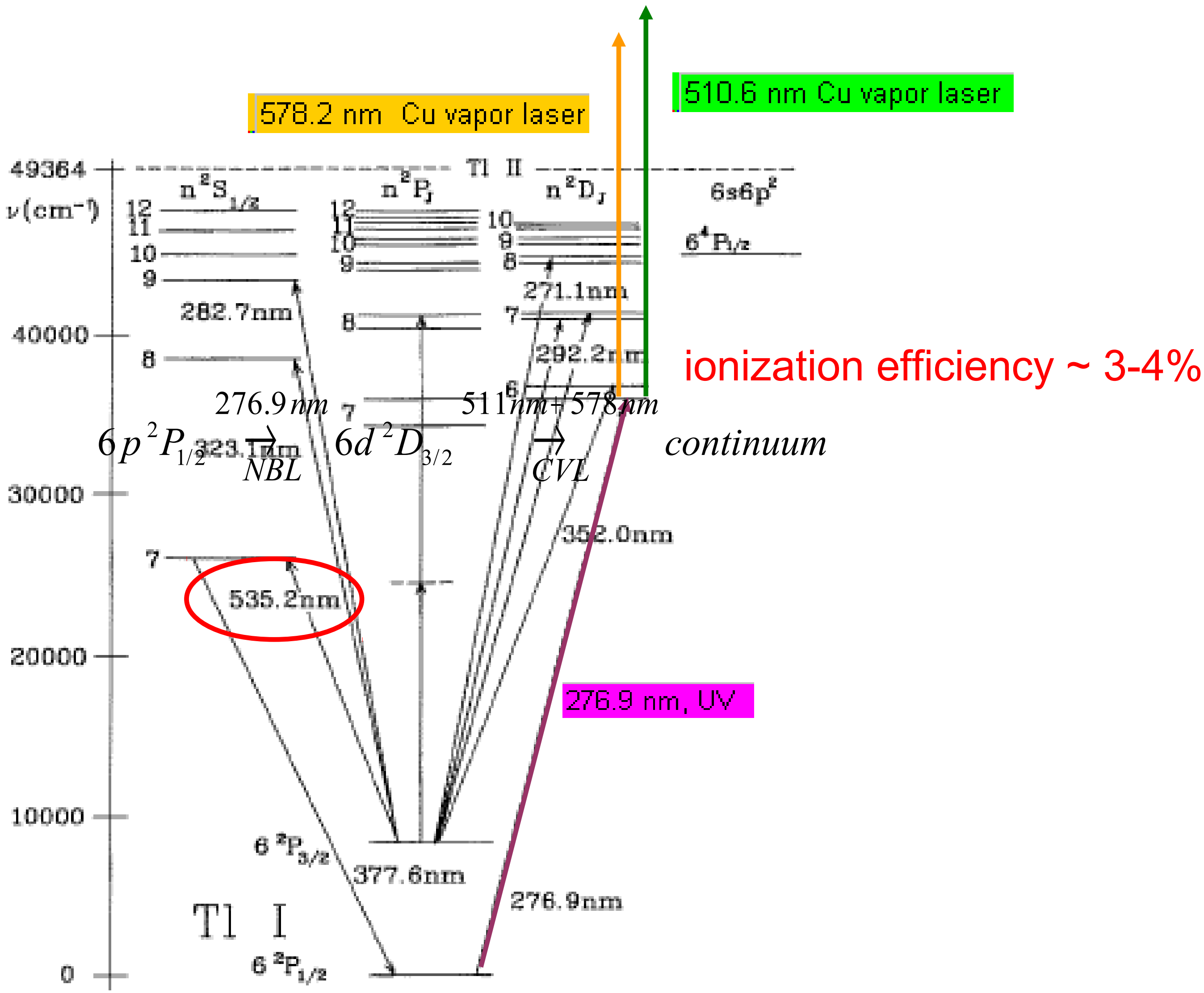


Fig. 1. Energy-level diagram of Tl I with the investigated transitions

Before our experiments:

^{183}Tl, I=1/2, $T_{1/2}$=6.9 s	^{184}Tl, I=7, $T_{1/2}$=11 s	^{185}Tl, I=1/2, $T_{1/2}$=19.5 s	^{186}Tl, I=7, $T_{1/2}$=27.5 s	^{187}Tl, I=1/2, $T_{1/2}$=51 s	^{188}Tl, I=7, $T_{1/2}$=71 s
?	?	^{185}Tl, I=9/2, $T_{1/2}$=1.8 s	^{186}Tl, I=10, $T_{1/2}$=2.9 s	^{187}Tl, I=9/2, $T_{1/2}$=15.6 s	^{188}Tl, I=9, $T_{1/2}$=0.04 s

^{189}Tl, I=1/2, $T_{1/2}$=2.6 m	^{190}Tl, I=7, $T_{1/2}$=3.7 m	^{191}Tl, I=1/2, $T_{1/2}$=2.2 m	^{192}Tl, I=7, $T_{1/2}$=10.8 m	^{193}Tl, I=1/2, $T_{1/2}$=21.6 m	^{194}Tl, I=7, $T_{1/2}$=32.8 m
^{189}Tl, I=9/2, $T_{1/2}$=84 s	^{190}Tl, I=2, $T_{1/2}$=2.6 m	^{191}Tl, I=9/2, $T_{1/2}$=5.2 m	^{192}Tl, I=2, $T_{1/2}$=9.6 m	^{193}Tl, I=9/2, $T_{1/2}$=2.1 m	^{194}Tl, I=2, $T_{1/2}$=33 m

^{195}Tl, I=1/2, $T_{1/2}$=1.16 h	^{196}Tl, I=7, $T_{1/2}$=1.41 h	^{197}Tl, I=1/2, $T_{1/2}$=2.84 h	^{198}Tl, I=7, $T_{1/2}$=1.87 h	^{199}Tl, I=1/2, $T_{1/2}$=7.42 h	^{200}Tl, I=2, $T_{1/2}$=26.1 h
^{195}Tl, I=9/2, $T_{1/2}$=3.6 s	^{196}Tl, I=2, $T_{1/2}$=1.84 h	^{197}Tl, I=9/2, $T_{1/2}$=0.54 s	^{198}Tl, I=2, $T_{1/2}$=5.3 h	^{199}Tl, I=9/2, $T_{1/2}$=0.028 s	

^{201}Tl, I=1/2, $T_{1/2}$=72.9 h	^{202}Tl, I=2, $T_{1/2}$=12.23 d	^{203}Tl, I=1/2, stable
^{201}Tl, I=9/2, $T_{1/2}$=0.002 s		

- g.s.
- m.s., I=2
- m.s., I=9/2
- unknown

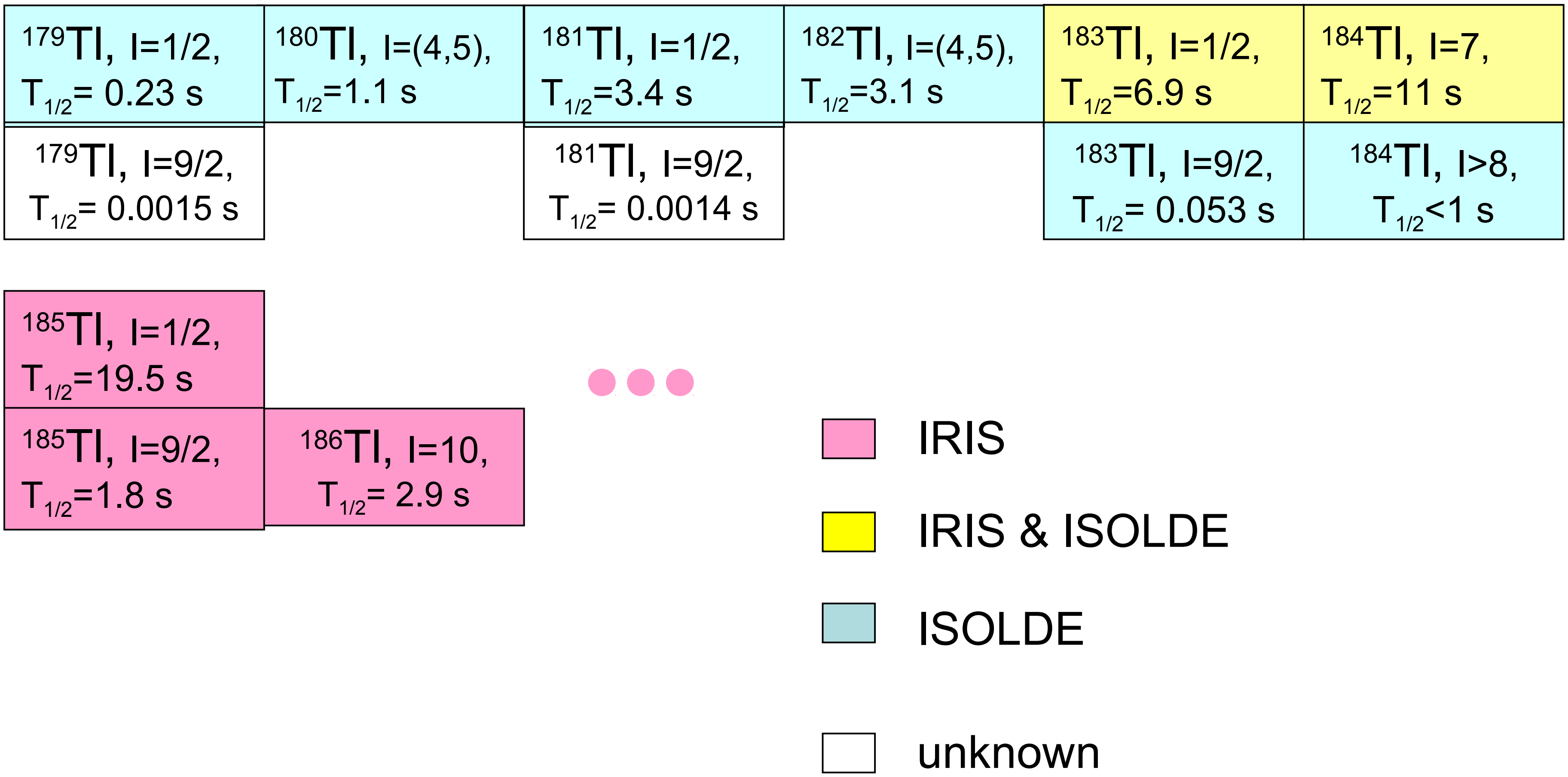
g.s., m.s. I=2, m.s. I=9/2: measured previously for $6p\,^2P_{3/2} \rightarrow 7s\,^2S_{1/2}$ transition (535.2 nm)

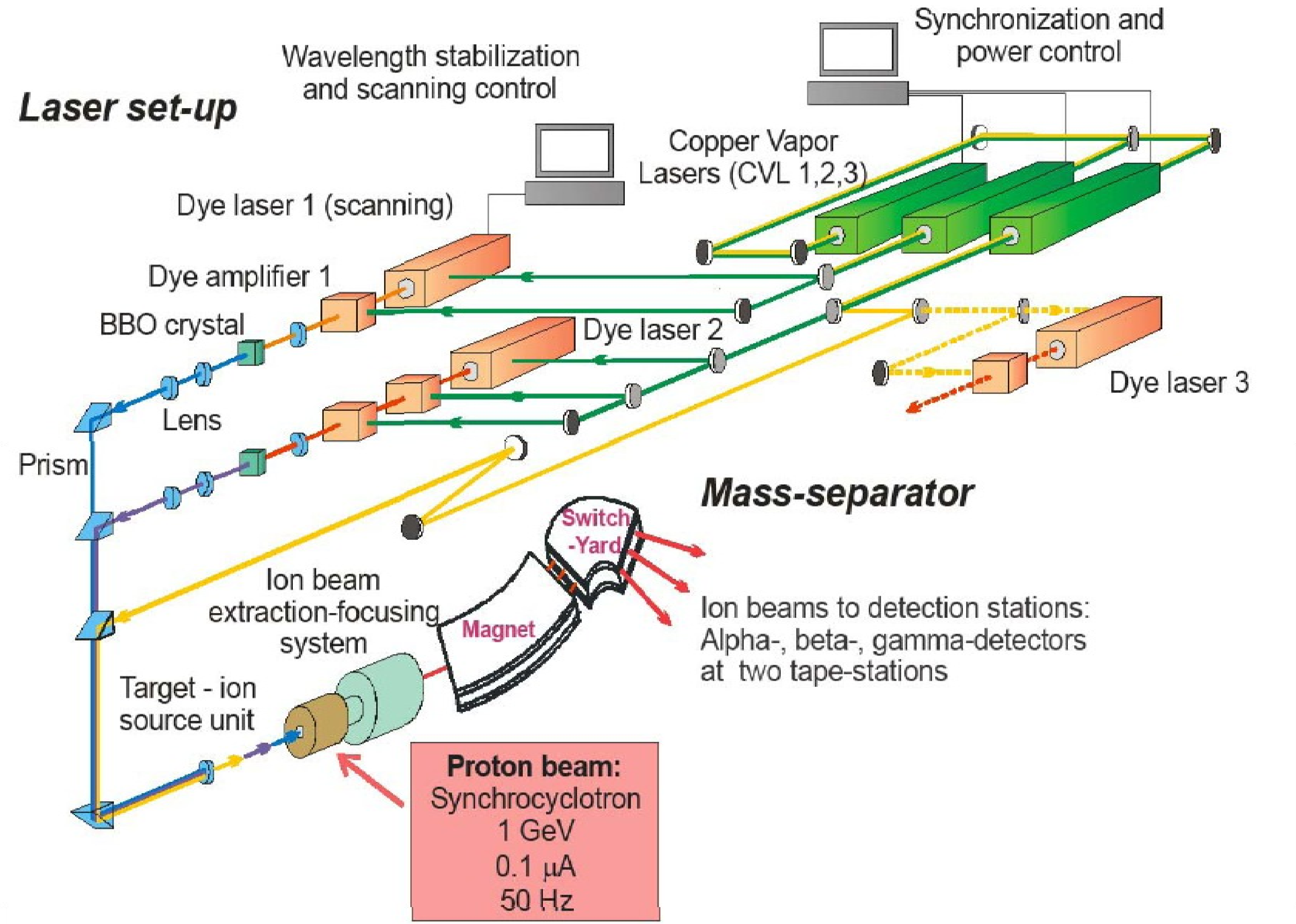
^{183}Tl, I=1/2, $T_{1/2}$=6.9 s	^{184}Tl, I=7, $T_{1/2}$=11 s	^{185}Tl, I=1/2, $T_{1/2}$=19.5 s	^{186}Tl, I=7, $T_{1/2}$=27.5 s	^{187}Tl, I=1/2, $T_{1/2}$=51 s	^{188}Tl, I=7, $T_{1/2}$=71 s
?	?	^{185}Tl, I=9/2, $T_{1/2}$=1.8 s	^{186}Tl, I=10, $T_{1/2}$=2.9 s	^{187}Tl, I=9/2, $T_{1/2}$=15.6 s	^{188}Tl, I=9, $T_{1/2}$=0.04 s
^{189}Tl, I=1/2, $T_{1/2}$=2.6 m	^{190}Tl, I=7, $T_{1/2}$=3.7 m	^{191}Tl, I=1/2, $T_{1/2}$=2.2 m	^{192}Tl, I=7, $T_{1/2}$=10.8 m	^{193}Tl, I=1/2, $T_{1/2}$=21.6 m	^{194}Tl, I=7, $T_{1/2}$=32.8 m
^{189}Tl, I=9/2, $T_{1/2}$=84 s	^{190}Tl, I=2, $T_{1/2}$=2.6 m	^{191}Tl, I=9/2, $T_{1/2}$=5.2 m	^{192}Tl, I=2, $T_{1/2}$=9.6 m	^{193}Tl, I=9/2, $T_{1/2}$=2.1 m	^{194}Tl, I=2, $T_{1/2}$=33 m
^{195}Tl, I=1/ $T_{1/2}$=1.16 h				^{199}Tl, I=1/2, $T_{1/2}$=7.42 h	^{200}Tl, I=2, $T_{1/2}$=26.1 h
^{195}Tl, I=9 $T_{1/2}$=3.6 s	$T_{1/2}$=1.84 h	$T_{1/2}$=0.54 s	$T_{1/2}$=5.3 h	*^{199}Tl, I=9/2, $T_{1/2}$=0.028 s*	
^{201}Tl, I=1/2, $T_{1/2}$=72.9 h	^{202}Tl, I=2, $T_{1/2}$=12.23 d	^{203}Tl, I=1/2, stable	. . .	^{207}Tl, I=1/2, $T_{1/2}$=4.77 m	
^{201}Tl, I=9/2, $T_{1/2}$=0.002 s					

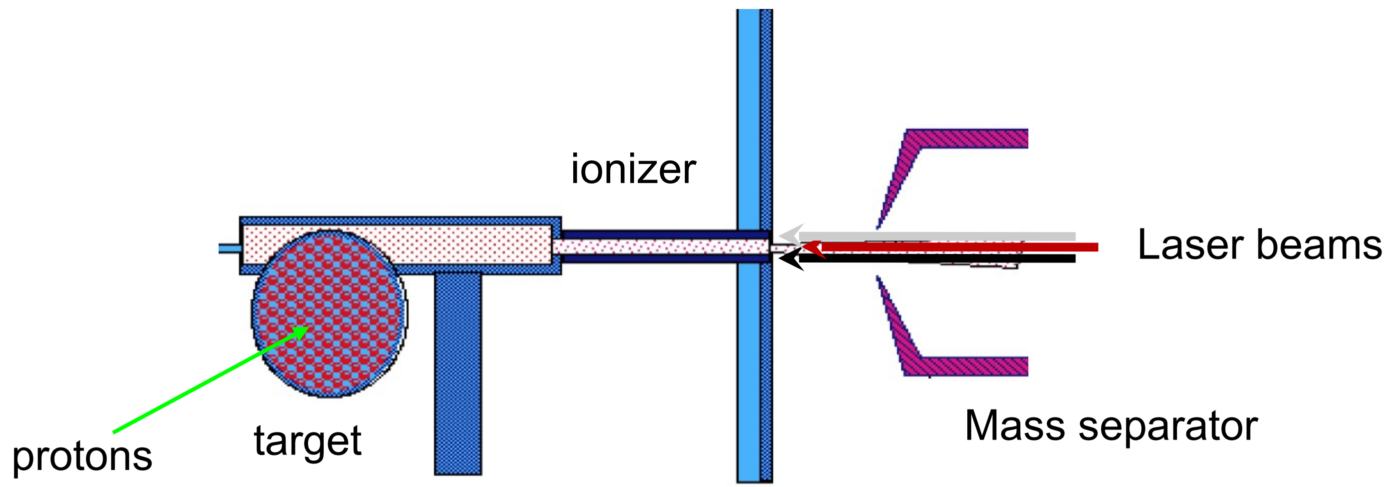
repeated for another atomic transition $6p\,^2P_{1/2} \rightarrow 6d\,^2D_{3/2}$ (276.9 nm)

for King-plot calibration

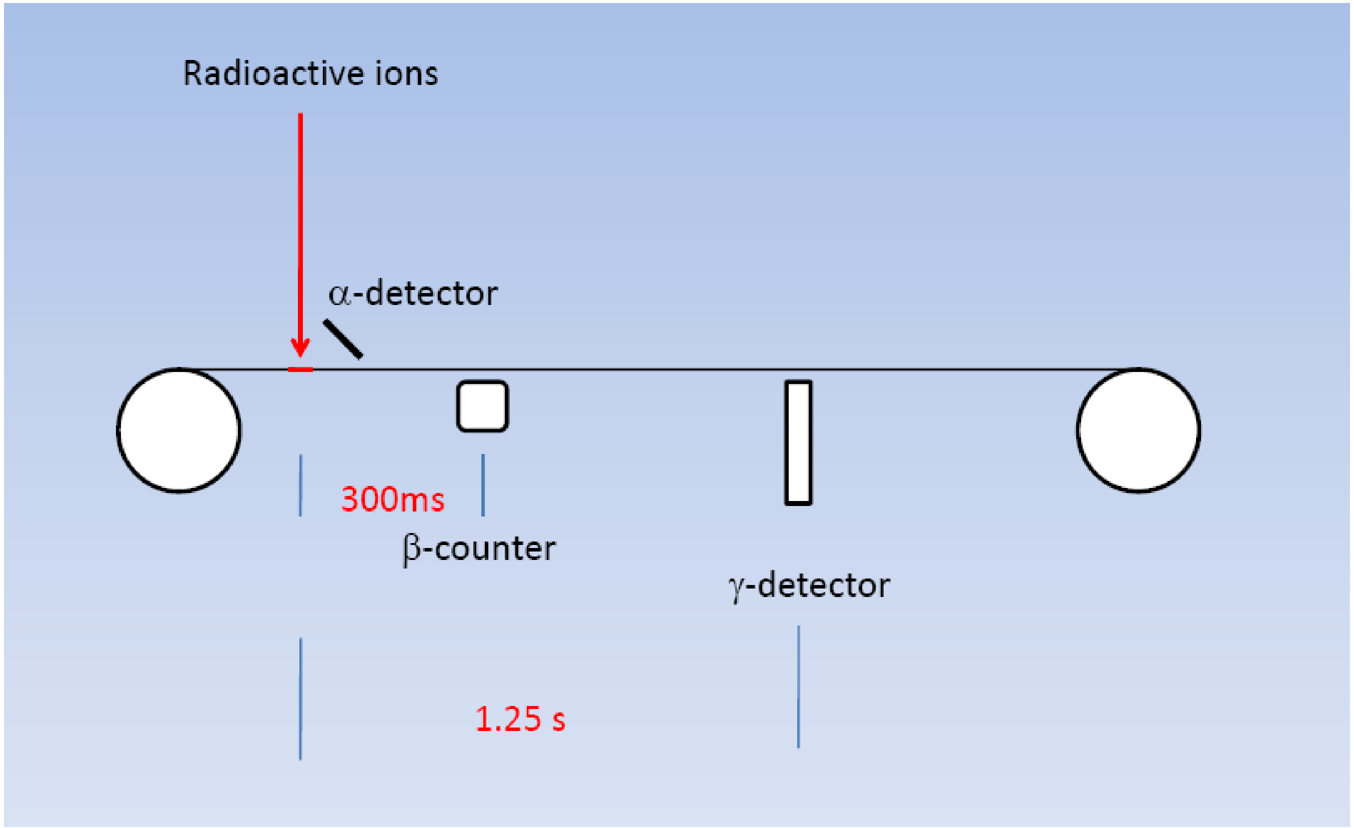
measured for the first time

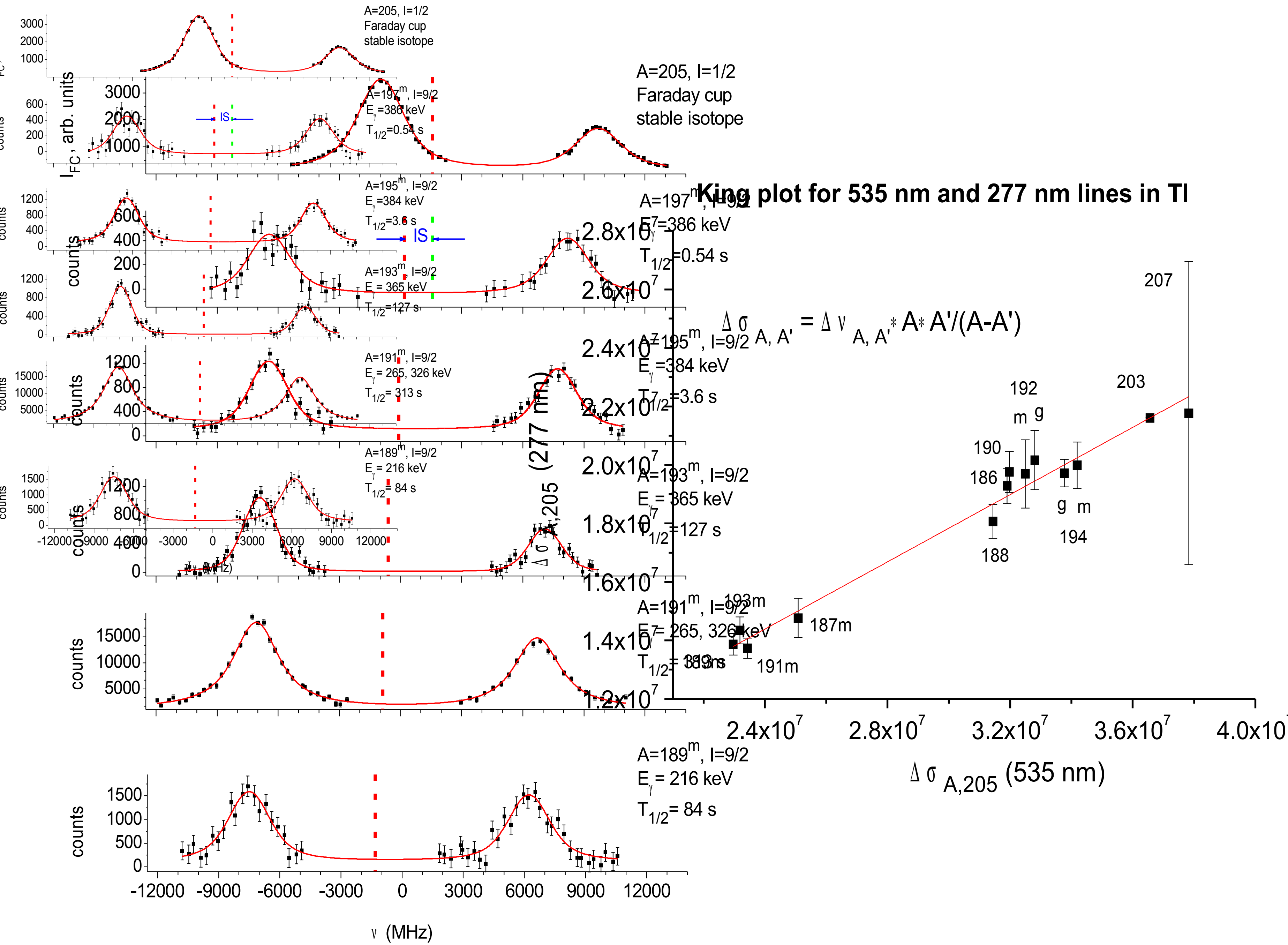

^{179}Tl, I=1/2, $T_{1/2}$= 0.23 s
^{180}Tl, I=(4,5), $T_{1/2}$=1.1 s
^{181}Tl, I=1/2, $T_{1/2}$=3.4 s
^{182}Tl, I=(4,5), $T_{1/2}$=3.1 s
^{183}Tl, I=1/2, $T_{1/2}$=6.9 s
^{184}Tl, I=7, $T_{1/2}$=11 s
^{179}Tl, I=9/2, $T_{1/2}$= 0.0015 s
^{181}Tl, I=9/2, $T_{1/2}$= 0.0014 s
^{183}Tl, I=9/2, $T_{1/2}$= 0.053 s
^{184}Tl, I>8, $T_{1/2}$<1 s
^{185}Tl, I=1/2, $T_{1/2}$=19.5 s
^{185}Tl, I=9/2, $T_{1/2}$=1.8 s
^{186}Tl, I=10, $T_{1/2}$= 2.9 s
IRIS
IRIS & ISOLDE
ISOLDE
unknown


Laser set-up
Wavelength stabilization and scanning control
Synchronization and power control
Copper Vapor Lasers (CVL 1,2,3)
Dye laser 1 (scanning)
Dye amplifier 1
BBO crystal
Dye laser 2
Dye laser 3
Lens
Prism
Mass-separator
Switch -Yard
Magnet
Ion beam extraction-focusing system
Ion beams to detection stations: Alpha-, beta-, gamma-detectors at two tape-stations
Target - ion source unit
Proton beam:
Synchrocyclotron
1 GeV
0.1 μA
50 Hz

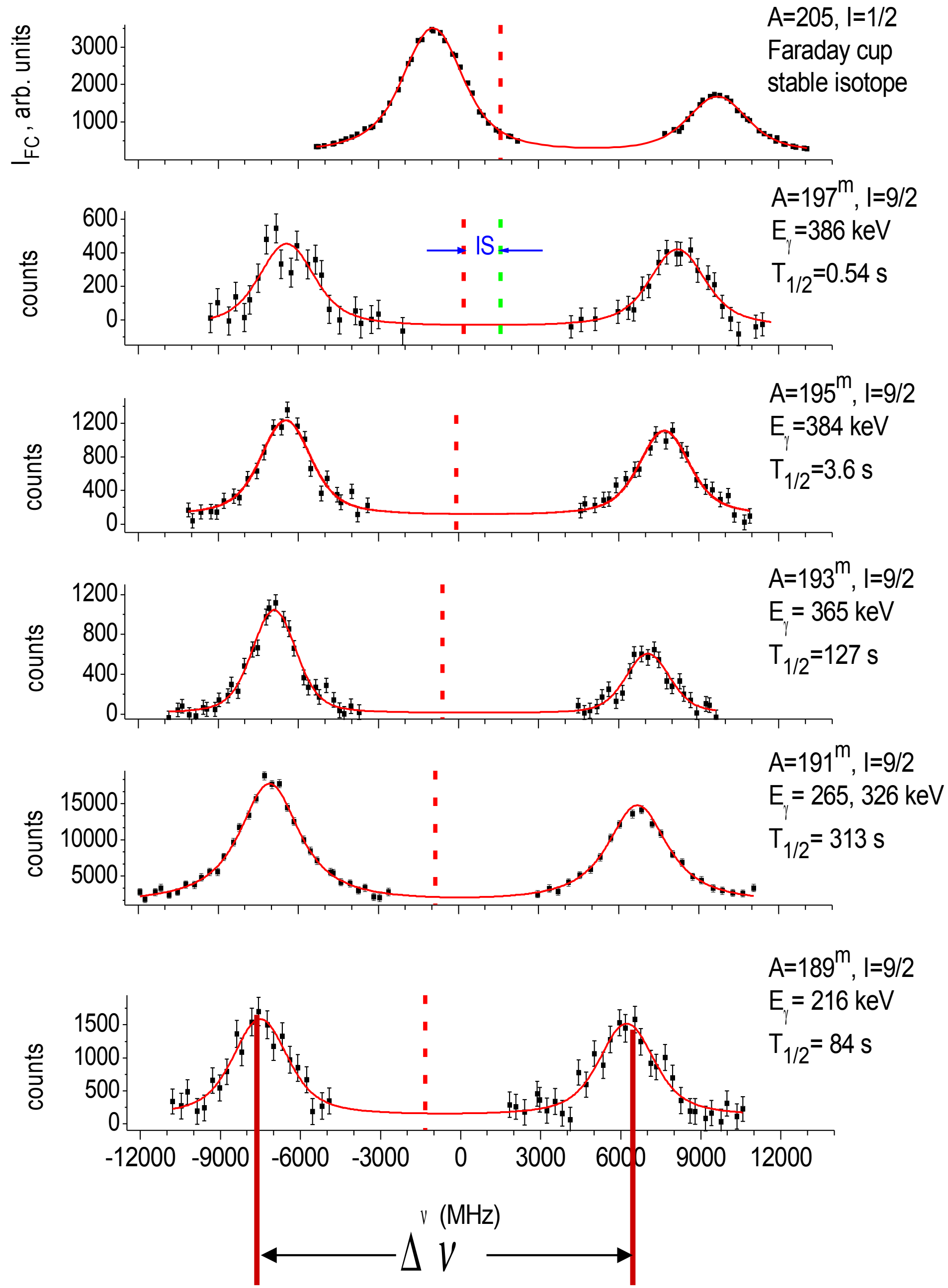


Laser Ion Source (LIS)


Radioactive ions
α-detector
300ms
β-counter
γ-detector
1.25 s



King plot for 535 nm and 277 nm lines in Tl
$\Delta\sigma_{A,A'} = \Delta\nu_{A,A'} * A * A'/(A-A')$
$\Delta\sigma_{A,205}$ (535 nm)
$\Delta\sigma_{A,205}$ (277 nm)
207
203
192
m g
190
186
188
g m
194
193m
187m
191m
189m
A=205, I=1/2
Faraday cup
stable isotope
I_{FC}, arb. units
A=197^m, I=9/2
E_γ=386 keV
$T_{1/2}$=0.54 s
IS
A=195^m, I=9/2
E_γ=384 keV
$T_{1/2}$=3.6 s
A=193^m, I=9/2
E_γ = 365 keV
$T_{1/2}$=127 s
A=191^m, I=9/2
E_γ= 265, 326 keV
$T_{1/2}$= 313 s
A=189^m, I=9/2
E_γ= 216 keV
$T_{1/2}$= 84 s
counts
ν (MHz)



$$\Delta\nu = a \times \frac{2I+1}{2}$$

$$a \propto \frac{\mu}{I}$$

$$\frac{\mu_A}{I_A} = const$$

$$\frac{\mu_A}{I_A \times a_A} \neq const$$

$$\mu_A = \mu_{205} \times \frac{I_A}{I_{205}} \times \frac{a_A}{a_{205}}$$

HFA:

$${}^{A_1}\Delta^{A_2} = \frac{a_1 \times I_1}{\mu_1} \times \frac{\mu_2}{a_2 \times I_2} - 1$$

$${}^{A_1}\Delta^{A_2} = \frac{a_1 \times I_1}{\mu_1} \times \frac{\mu_2}{a_2 \times I_2} - 1$$

$$\mu_A = \mu_{205} \times \frac{I_A}{I_{205}} \times \frac{a_A}{a_{205}} \times (1 + {}^{205}\Delta^{A})$$

$$a = a_{point}(1 + \varepsilon) \Longrightarrow {}^{A_1}\Delta^{A_2} \approx (\varepsilon_{A_1} - \varepsilon_{A_2})$$

$$\varepsilon \propto < r^2 >_m$$

DHFA:

$$\rho^{A}_{n_1 l_1, n_2 l_2} = \frac{a^{A}_{n_1 l_1}}{a^{A}_{n_2 l_2}},$$

Ratio $\rho^{A}_{l_1,l_2}$ can have a different value for different isotopes because the atomic states with different *n*, *l* have different sensitivity to the nuclear magnetization distribution.

Our case: we have studied state with $p_{1/2}$ valence electron; previously state with $s_{1/2}$ valence electron has been studied

$${}^{n_1 l_1}_{A_1}\Delta^{n_2 l_2}_{A_2} = \frac{\rho^{A_1}_{n_1 l_1, n_2 l_2}}{\rho^{A_2}_{n_1 l_1, n_2 l_2}} - 1 = {}^{A_1}\Delta^{A_2}(n_1 l_1) - {}^{A_1}\Delta^{A_2}(n_2 l_2)$$

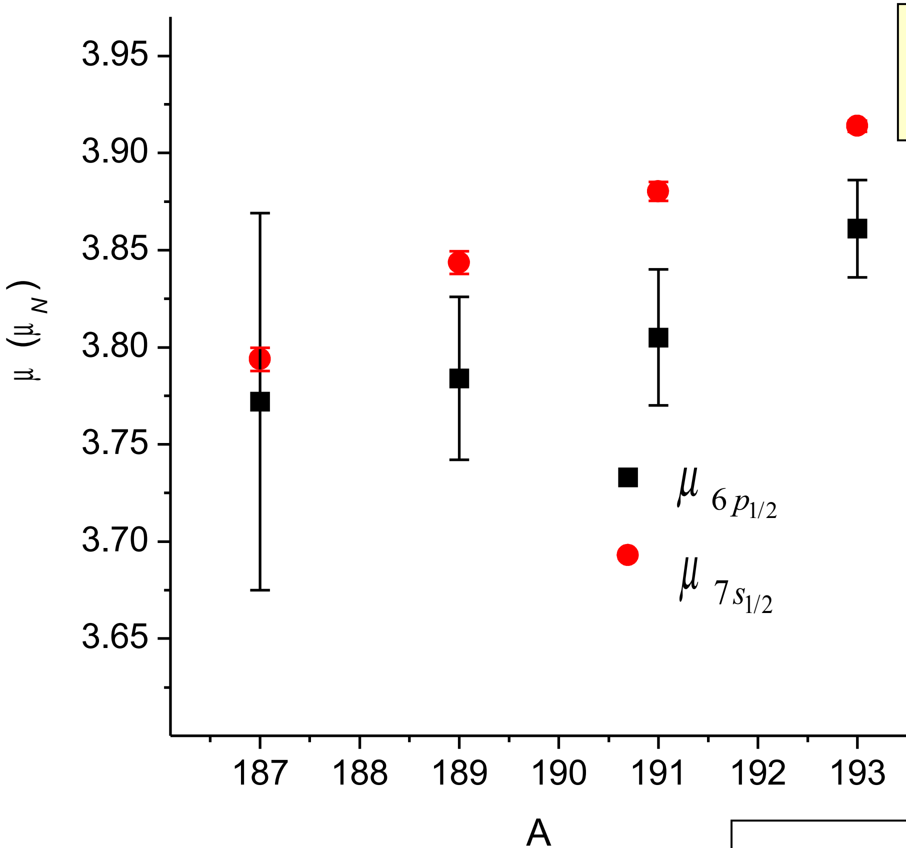
$${}^{205}\Delta^{203}_{6P_{1/2}} = 1.050(15)\cdot 10^{-4}$$

$${}^{205}\Delta^{203}_{7S_{1/2}} = 3.4(15)\times 10^{-4}$$

$${}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{203} = 2.4(1.5)\times 10^{-4}$$

Ratio of the electron density at the nucleus for $p_{1/2}$ state and $s_{1/2}$ state: ; $(\alpha Z)^2 = 0.34$ for *Z*=81, so one can expect: $\frac{{}^{A_1}\Delta^{A_2}(p_{1/2})}{{}^{A_1}\Delta^{A_2}(s_{1/2})}$; 0.3

$$\mu_{nl} \equiv \mu_{205} \times \frac{I_A}{I_{205}} \times \frac{a_A(nl)}{a_{205}(nl)} \quad \Rightarrow \quad \mu_A = \mu_{nl} \times (1 + {}^{205}\Delta^{A}_{nl})$$



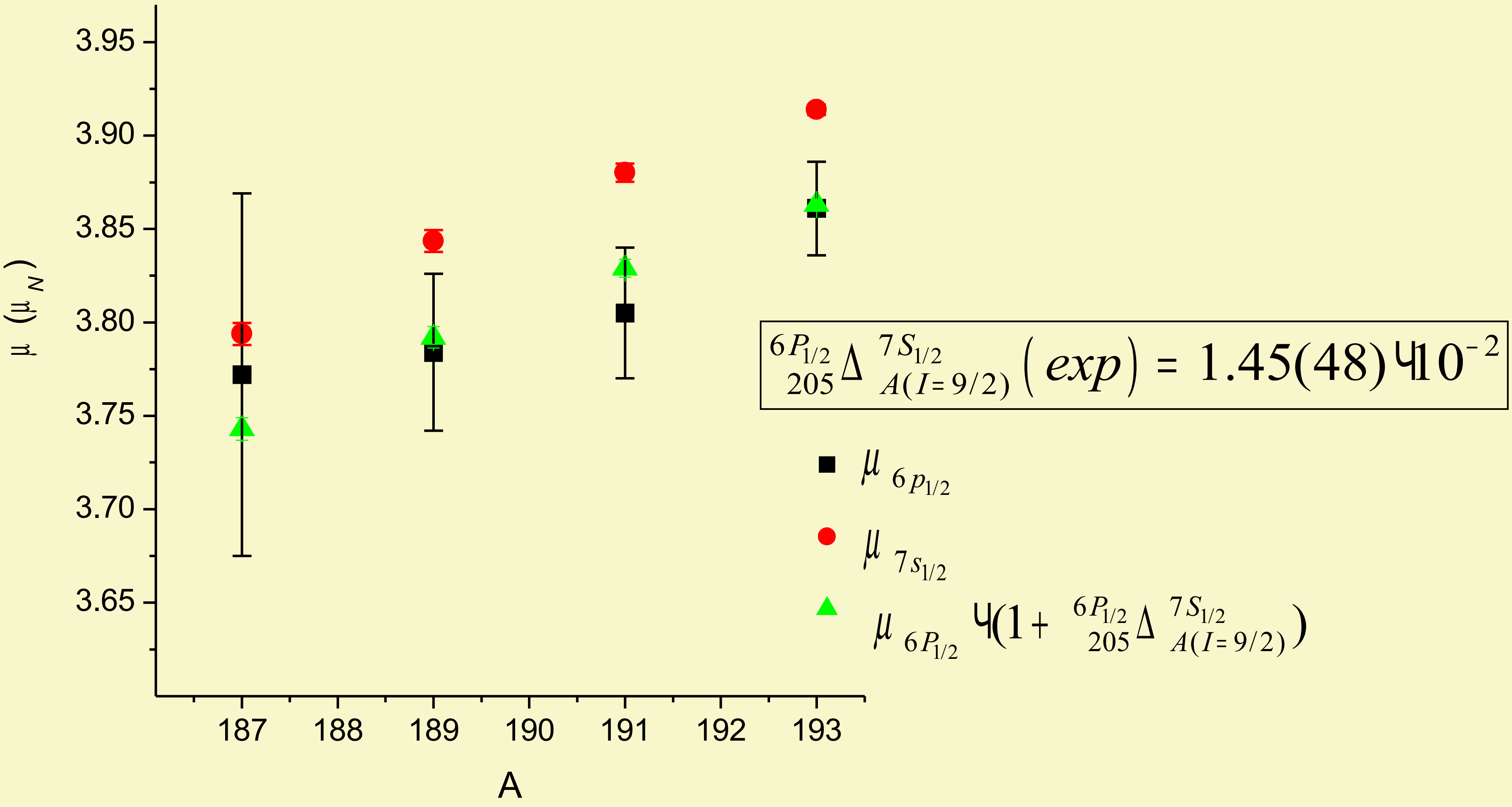
$$\mu_{7S_{1/2}}(A) = \mu_{6P_{1/2}}(A) \times (1 + {}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{A})$$

A	${}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{A}$
187	$0.5(2.6)\times10^{-2}$
189	$1.5(1.1)\times10^{-2}$
191	$1.67(93)\times10^{-2}$
193	$1.36(66)\times10^{-2}$

large errors prevent to trace isotopic dependence of DHFA

$$\text{mean}: {}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{A(I=9/2)}(exp) = 1.45(48)\times10^{-2}$$

Magnetic moments for Tl isomers with I=9/2



DHFA calculation
Atomic part: atomic many-body technique
(relativistic “coupled-cluster” approach) by A.-M. Mårtensson-Pendrill

$$\varepsilon = b_{2s}\cdot\lambda_m\cdot d_2, \quad \lambda_m = \langle r^2\rangle_m \cdot \left(1 + \frac{b_{4s}\cdot d_4}{b_{2s}\cdot d_2}\cdot\frac{\langle r^4\rangle}{\langle r^2\rangle} + \ldots\right) = k_m\cdot\langle r^2\rangle_m$$

Single shell-model configuration:

(in our case:
pure $h_{9/2}$ intruder state)

$$d_{2n} = C_s\cdot\left(1 + \frac{2n}{2n+3}\cdot\zeta\right) + \frac{3}{2n+3}\cdot\left(1 - C_s\right).$$

$$\zeta = \frac{2I+3}{4I} \qquad C_s = \frac{g_s}{g_I}\cdot\frac{g_I - g_L}{g_s - g_L}$$

$${}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{A(I=9/2)}(theor) = 1.2\cdot 10^{-2} \qquad {}^{6P_{1/2}}_{205}\Delta^{7S_{1/2}}_{A(I=9/2)}(exp) = 1.45(48)\cdot 10^{-2}$$

$$\frac{{}^{A_1}\Delta^{A_2}(p_{1/2})}{{}^{A_1}\Delta^{A_2}(s_{1/2})}(theor) = 0.31 \quad (cf.:(\alpha Z)^2 = 0.34)$$

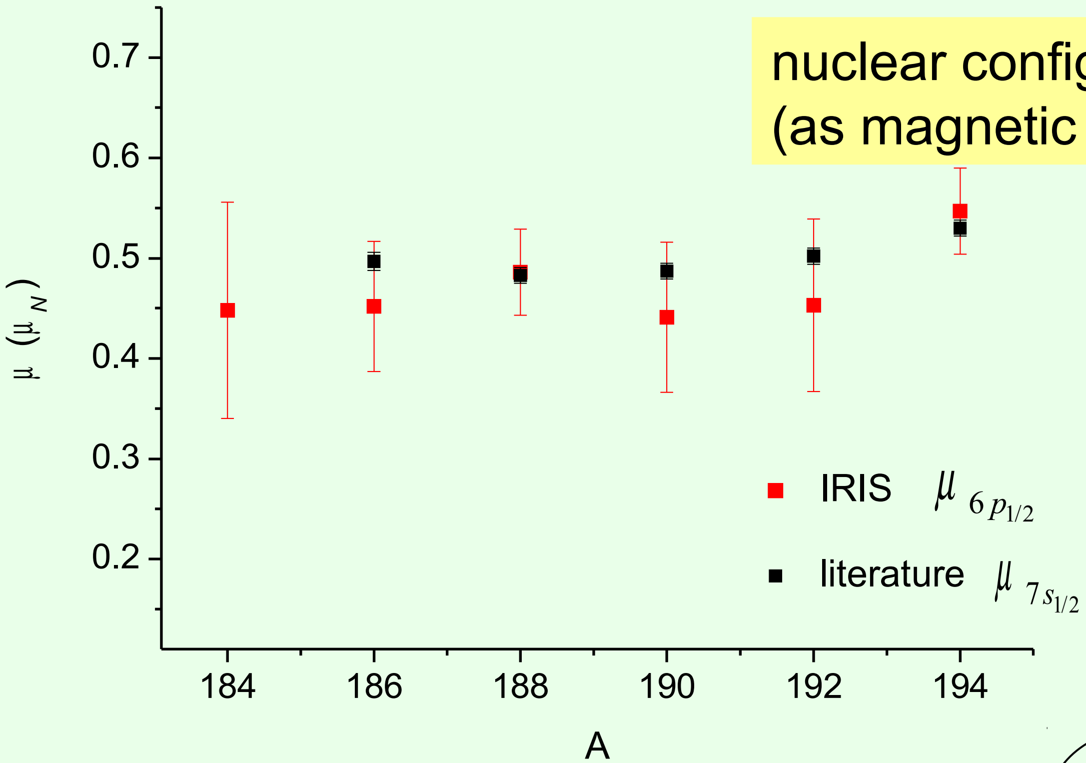
$${}^{205}\Delta^{203}_{6P_{1/2}} = 1.050(15)\cdot 10^{-4}$$

Magnetic moments for Tl isomers with I=9/2

A	μ (μ_N) (literature data)	μ (μ_N) with the new HFA correction
185		3.849(90)
187	3.7932(65)	3.712(27)
189	3.8776(63)	3.760(28)
191	3.9034(48)	3.785(28)
193	3.9482(39)	3.829(28)
195		3.898(38)
197		4.047(69)

$$\mu_A = \mu_{205} \times \frac{I_A}{I_{205}} \times \frac{a_A(nl)}{a_{205}(nl)} \times (1 + {}^{205}\Delta^{A}_{nl})$$

Magnetic moments for Tl isotopes with I=7 (without HFA)

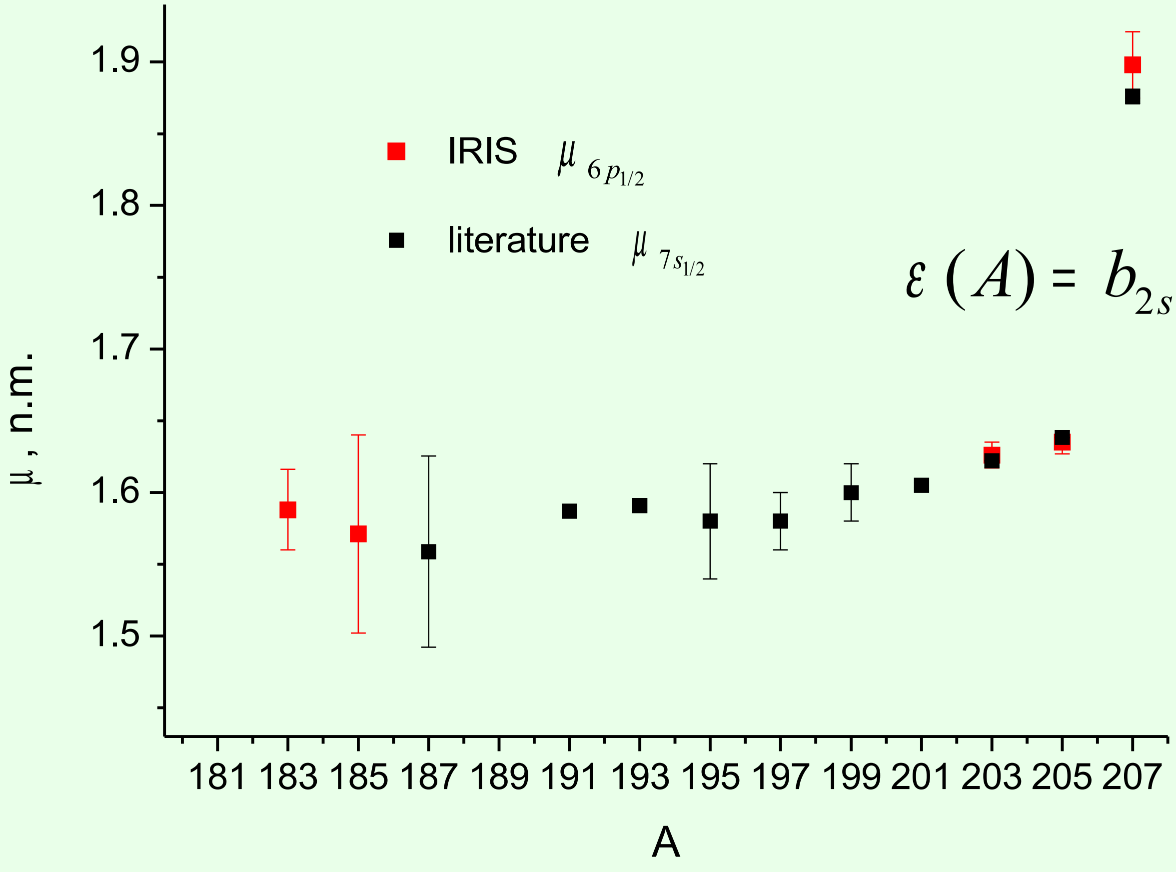


nuclear configuration part: independent of A (as magnetic moment constancy shows)

$$\varepsilon(A) = b_{2s} \times k_m \times \langle r^2 \rangle_m (A) \times d_2(A)$$

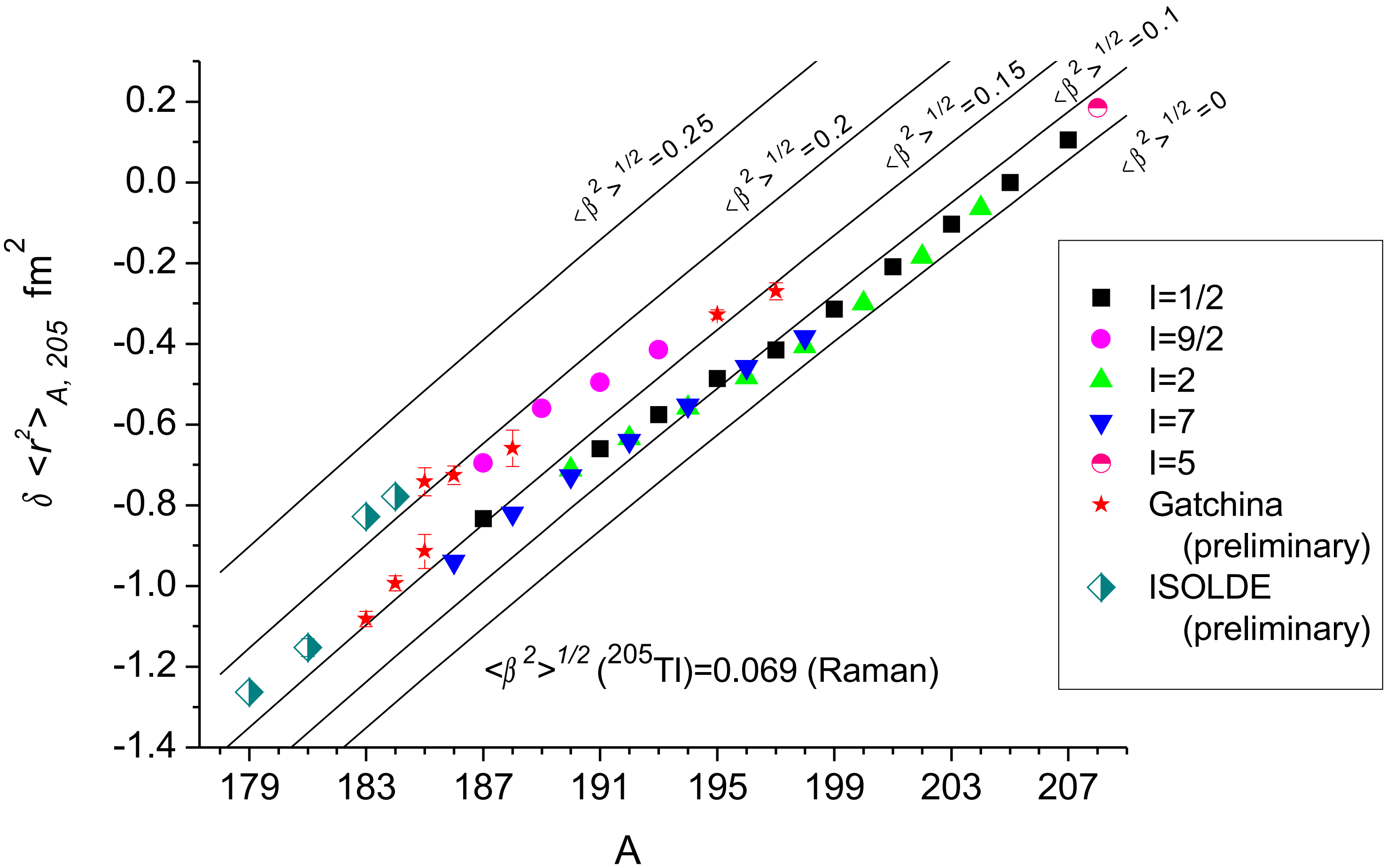
atomic part: independent of A

Magnetic moments for Tl isotopes with I=1/2 (without HFA)



$$\varepsilon(A) = b_{2s} \cdot k_m \cdot \langle r^2 \rangle_m (A) \cdot d_2(A)$$

1. Продемонстрирована работоспособность и эффективность новой лазерной установки на масс-сепараторе ИРИС.
2. Впервые измерена аномалия сверхтонкой структуры для изомеров таллия с *I*=9/2, что позволило, в частности, уточнить значения ранее измеренных магнитных моментов.
3. Показано, что современные атомные расчеты удовлетворительно описывают «электронные» факторы, необходимые для вычисления HFA.
4. Измерение DHFA в сочетании с современными атомными расчетами открывает возможность исследования распределения намагниченности для короткоживущих удаленных ядер.



$\delta <r^2>_{A, 205}$ fm^2
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
179
183
187
191
195
199
203
207
A
$<\beta^2>^{1/2}$=0.25
$<\beta^2>^{1/2}$=0.2
$<\beta^2>^{1/2}$=0.15
$<\beta^2>^{1/2}$=0.1
$<\beta^2>^{1/2}$=0
$<\beta^2>^{1/2}$ (^{205}Tl)=0.069 (Raman)
I=1/2
I=9/2
I=2
I=7
I=5
Gatchina (preliminary)
ISOLDE (preliminary)