Charge radii by collinear laser spectroscopy

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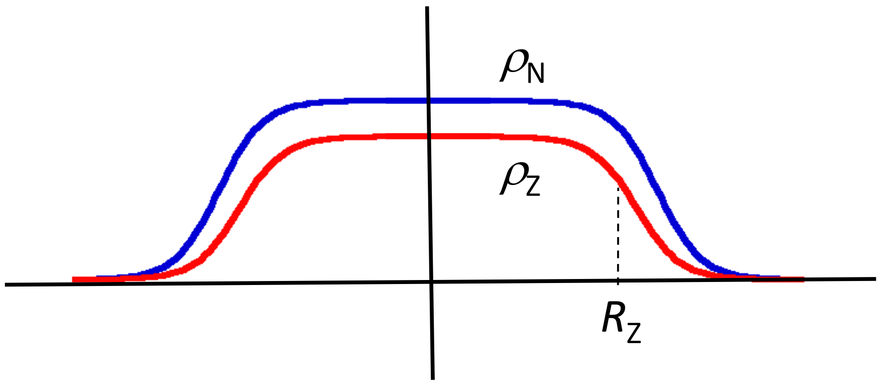
Outline

1. Charge radii and isotope shifts
2. Collinear laser spectroscopy to measure the isotope shifts
3. Example of some nuclides
4. Plan of collinear laser spectroscopy and in-gas jet laser spectroscopy at RIBF

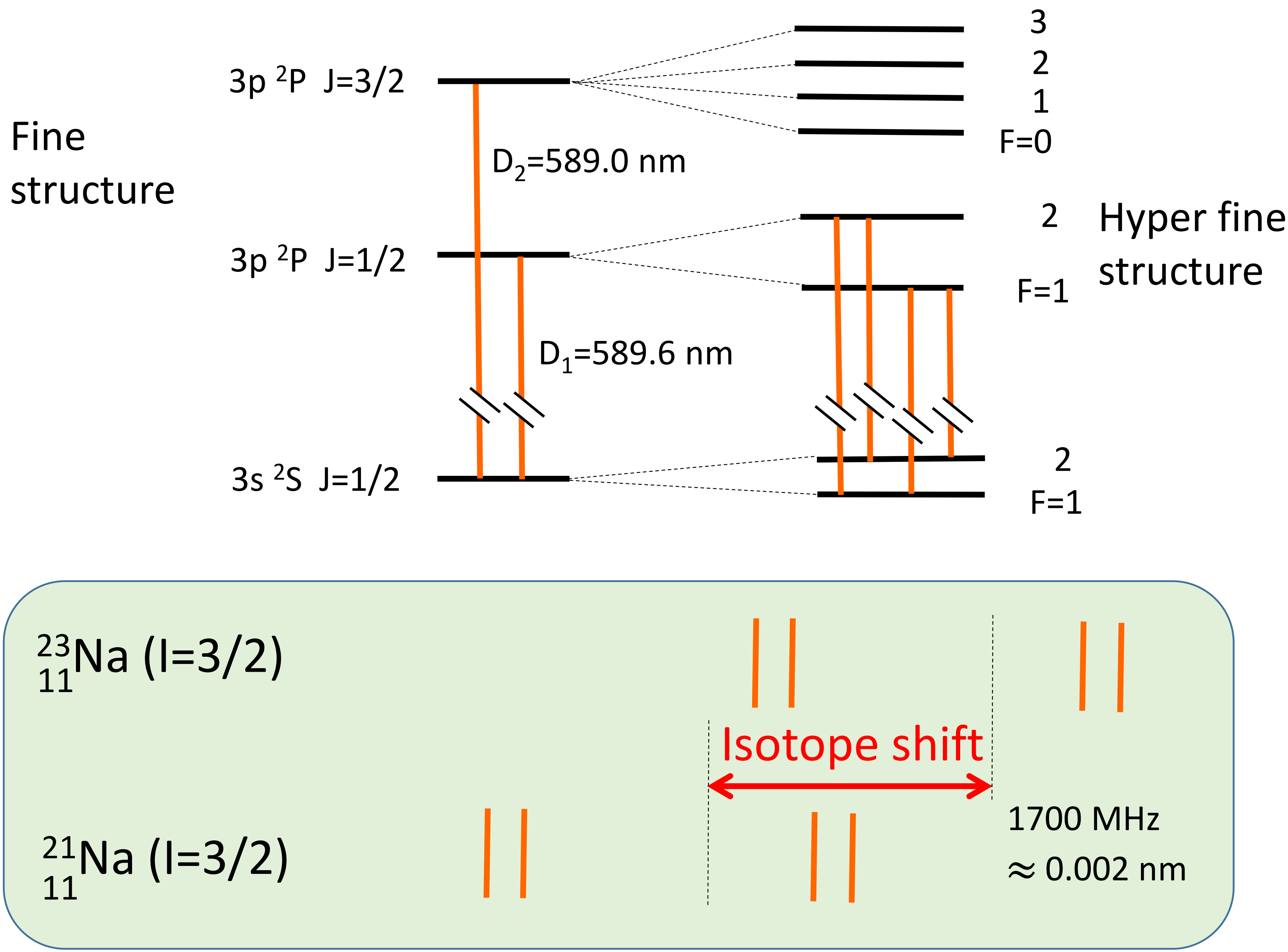


Mean square radius $$\langle r_Z^2 \rangle = \int \rho_Z(r) r^2 4\pi r^2 \, dr \Big/ \int \rho_Z(r) 4\pi r^2 \, dr$$

If $$\rho_Z = \frac{\rho_0}{[1 + \exp\{(r - R_Z)/a\}]}$$

$$R_Z \approx r_0 A^{\frac{1}{3}}$$

Then $$\langle r_Z^2 \rangle \cong \frac{3}{5} R_Z^2 \left[1 + \frac{3}{7}\pi^2 (a/R_Z)^2\right]$$



Fine structure
3p ^{2}P J=3/2
3p ^{2}P J=1/2
3s ^{2}S J=1/2
D$_2$=589.0 nm
D$_1$=589.6 nm
3
2
1
F=0
2
F=1
Hyper fine structure
2
F=1
$^{23}_{11}$Na (I=3/2)
Isotope shift
1700 MHz
≈ 0.002 nm
$^{21}_{11}$Na (I=3/2)

$$\delta\nu^{AA'} \equiv \nu^{A'} - \nu^{A}$$

$$\delta\nu^{AA'} = \delta\nu_{\mathrm{NMS}} + \delta\nu_{\mathrm{SMS}} + \delta\nu_{\mathrm{FS}}$$

$\delta\nu_{\mathrm{NMS}}$: Normal mass shift

$\delta\nu_{\mathrm{SMS}}$: Specific mass shift

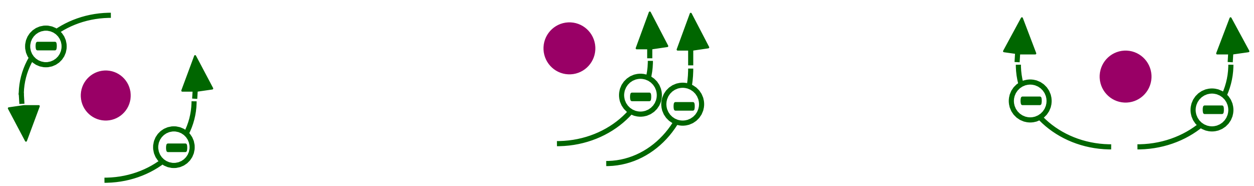
$\delta\nu_{\mathrm{FS}}$: Field shift

Element	Mass number	Transition	IS (MHz)	NMS (MHz)	SMS (MHz)	FS (MHz)
Na	21-23	3s-3p	1595	1147	447	1
Pb	206-208	$6p^2$-6p7s	2713	11	3	2699

- The <u>normal mass shift</u> is due to the reduced mass correction.

$$\delta\nu_{\mathrm{NMS}} = \nu_0 \times m_e \frac{M_{A'} - M_A}{M_{A'} M_A}$$

- The <u>specific mass shift</u> originates from the correlations in the motion of the electrons.



In general, reliable predictions from theory are not possible.

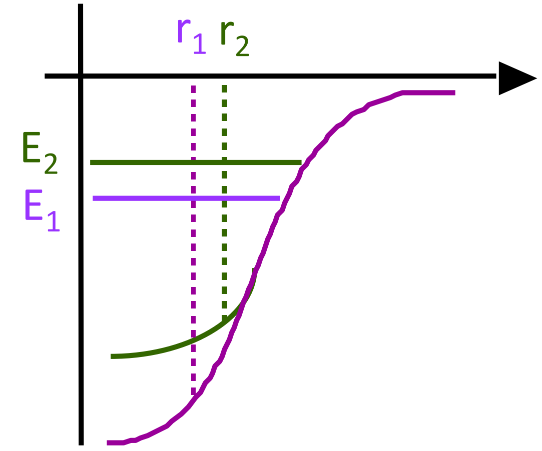
For ns-np transitions: $\delta\nu_{\mathrm{SMS}} = (0.3 \pm 0.9)\delta\nu_{\mathrm{NMS}}$

ns^2-nsp transitions: $\delta\nu_{\mathrm{SMS}} = (0.0 \pm 0.5)\delta\nu_{\mathrm{NMS}}$

Field shift

$$\delta\nu_{\mathrm{FS}} = F\left(\delta\langle r^2\rangle + \frac{C_2}{C_1}\delta\langle r^4\rangle + \frac{C_3}{C_1}\delta\langle r^6\rangle + \cdots\right)$$

$$\approx F\delta\langle r^2\rangle$$



F: Electronic factor

- *F* depends on transition, *Z*, (and *A*).
- For the determination of *F*, the most reliable approach is to use empirical data.
- Accuracy of *F* is typically 10 %.

Isotope shifts in atomic resonance lines

Z	Element	Mass number	Transition	Wave length (nm)	IS (MHz)
3	Li	6-7	2s-2p	670.8	10540
11	Na	23-24	3s-4p	330.3	720
19	K	39-40	4s-4p	769.9	1260
36	Kr	82-84	5s-5p	877.7	60
38	Sr	87-88	$5s^2$-5s5p	460.7	45
54	Xe	134-136	6s-6p	823.1	-90
55	Cs	133-134	6s-6p	852.1	36
70	Yb	174-176	$6s^2$-6s6p	398.8	510
80	Hg	198-199	$6s^2$-6s6p	253.7	-270
82	Pb	207-208	$6p^2$-6p7s	283.3	-1400

Linewidth in laser spectroscopy

Doppler broadening $$\Delta\nu_D = \frac{2\nu}{c}\sqrt{\frac{2\ln 2\, kT}{M}} \quad \approx 0.4 - 4\ \mathrm{GHz}$$

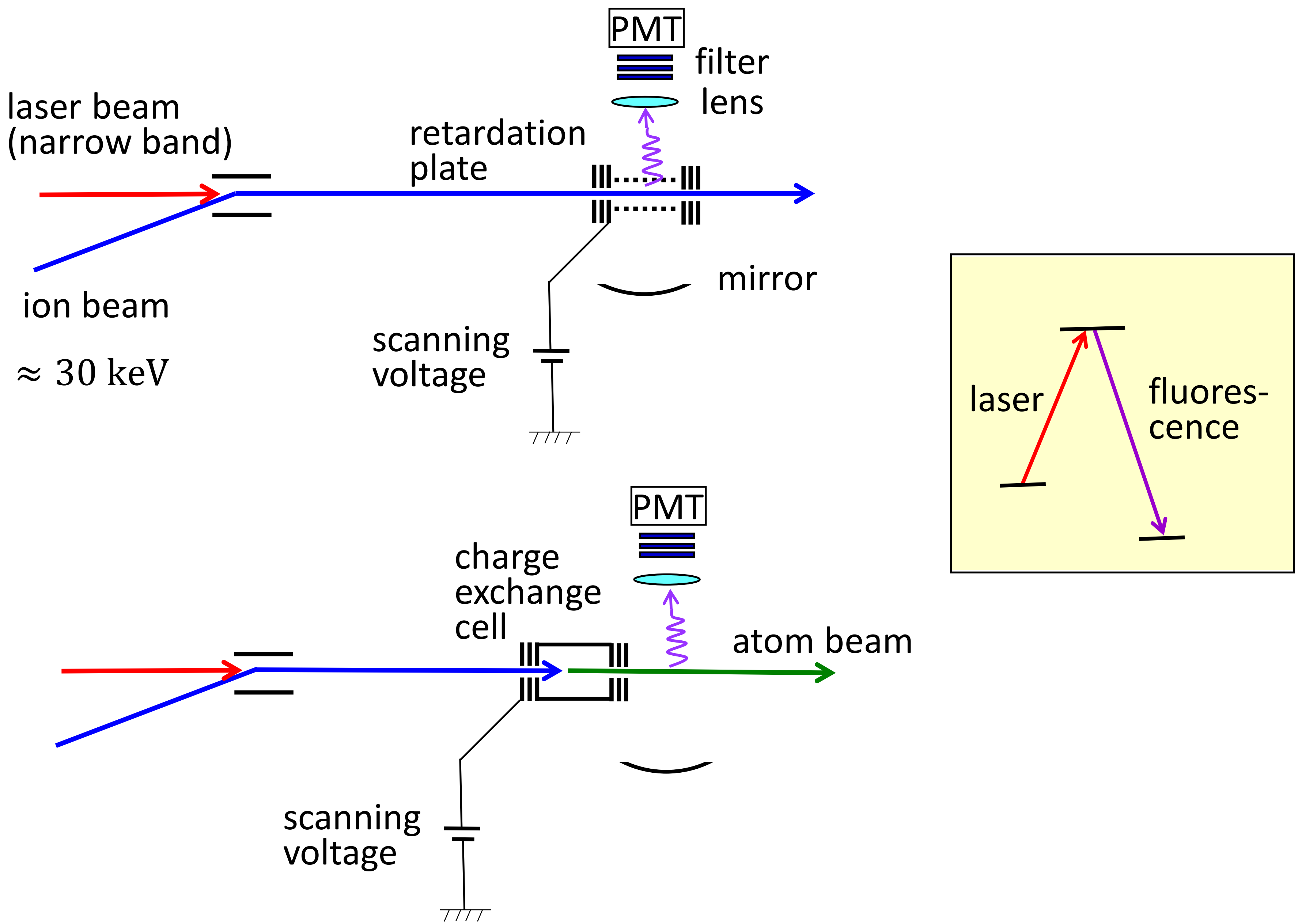
Natural linewidth $$\Delta\nu = \frac{1}{2\pi\tau} \quad \approx 10\ \mathrm{MHz}$$

Saturation broadening increases with laser intensity

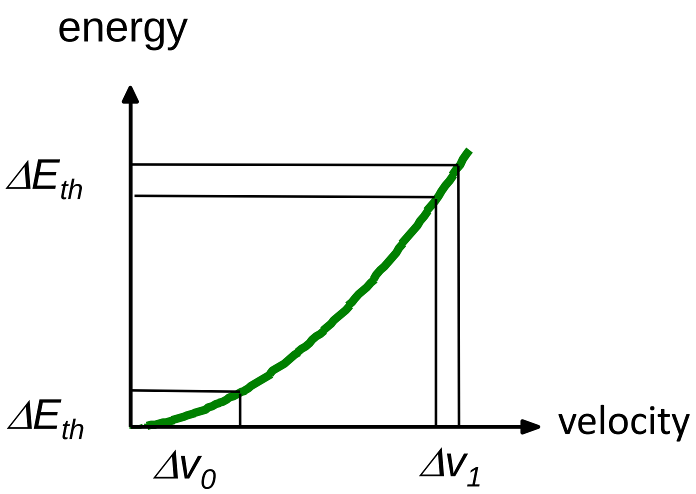
Pressure broadening $\approx 10\ \mathrm{MHz/Torr}$

Transit time broadening

Collinear laser spectroscopy setup



1. Doppler broadening



$$\frac{\Delta v_1}{\Delta v_0} = \sqrt{\frac{kT}{eU}}$$

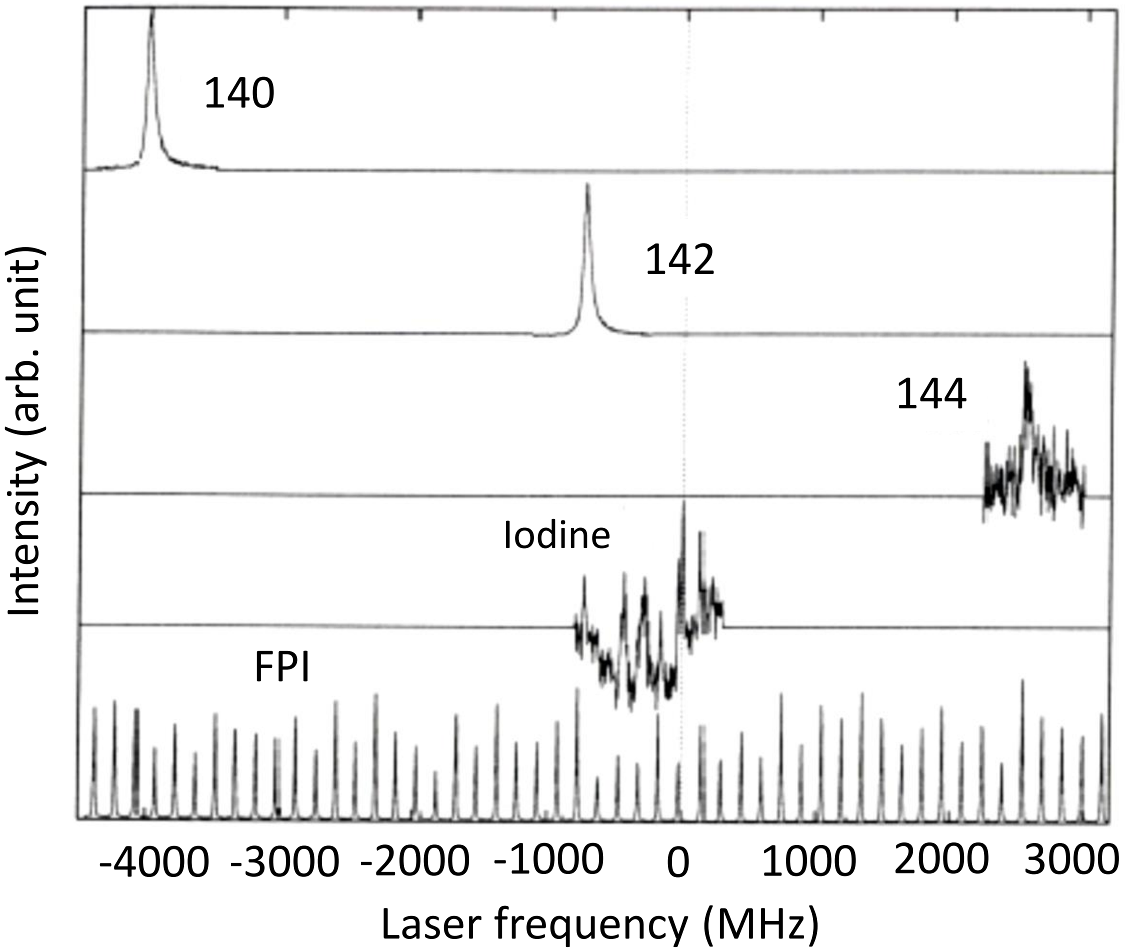
2 GHz @ 0 keV $\longrightarrow$ 2 MHz @ 30 keV

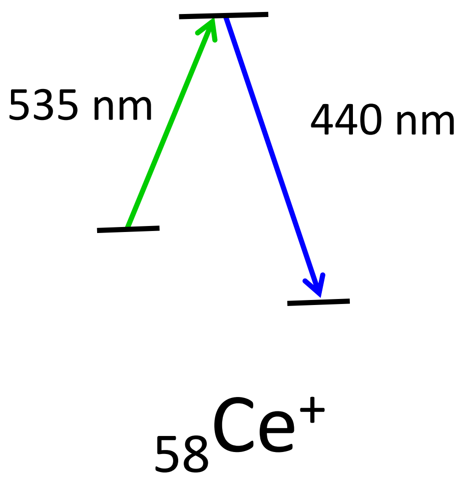
2. Doppler shift

$$\omega = \omega_0 \sqrt{\frac{1 - \frac{V}{c}}{1 + \frac{V}{c}}}$$

V: velocity of atoms

roughly 5 MHz per volt





line width $\approx$ 100 MHz

On-line collinear spectroscopy

- CERN-ISOLDE: $^{67-81}$Ga, $^{21-32}$Mg (β-NMR), ^{12}Be,
  $^{17-28}$Ne (collisional ionization), $^{202-205}$Fr (resonant ionization)
- Jyväskylä-IGISOL: $^{50-56}$Mn, $^{42-46}$Sc
- TRIUMF-ISAC: ^{74}Rb, ^{8,9,11}Li, Mg (β-NQR)
- MSU
- Mainz-TRIGA
- ANL-CARIB
- Orsay-ALTO

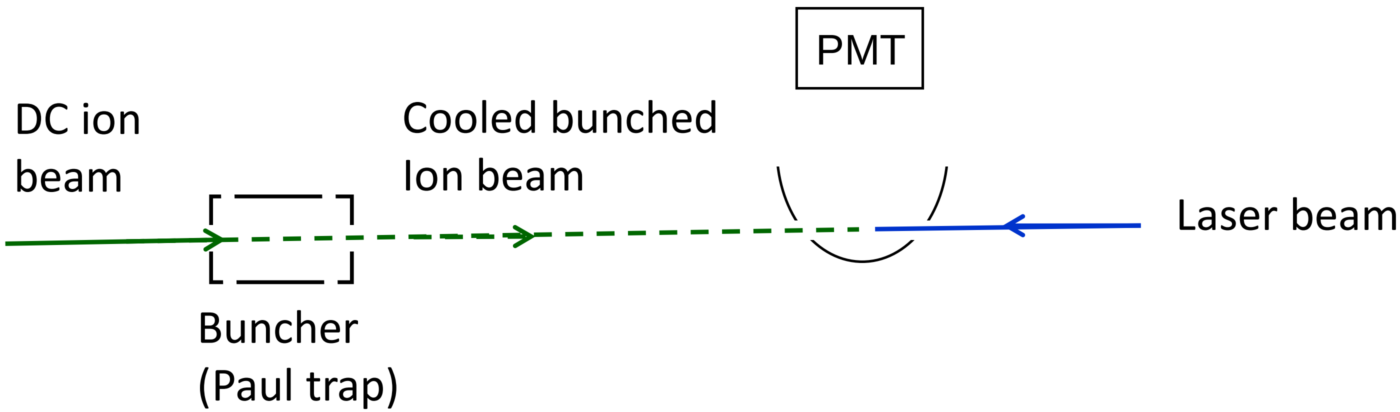
Efficiency of collinear spectroscopy

Ion beam transmission	0.5
Charge exchange	0.5
Population of lower state of excitation	0.01
Branching ratio of observed transition	0.5
Collection of photons	0.3
Filter transmission	0.2
Photomultiplier	0.2
Over all	1×10^{-5}

Back ground

Dark current of photomultiplier	100 cps
Scatter of laser	100 cps
Photons from ion beam	10 cps

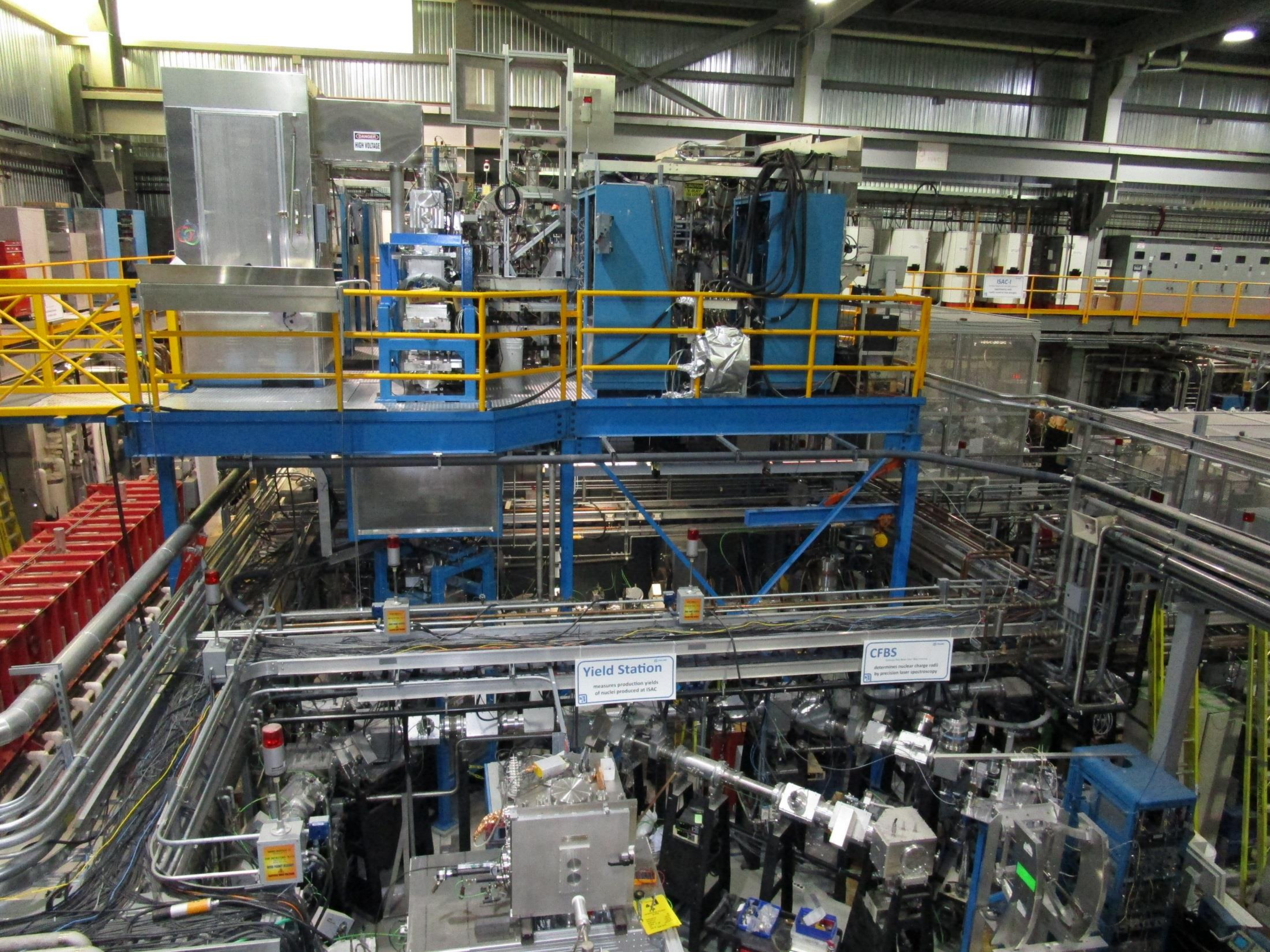
Required beam intensity $\approx 10^6$ atoms/s

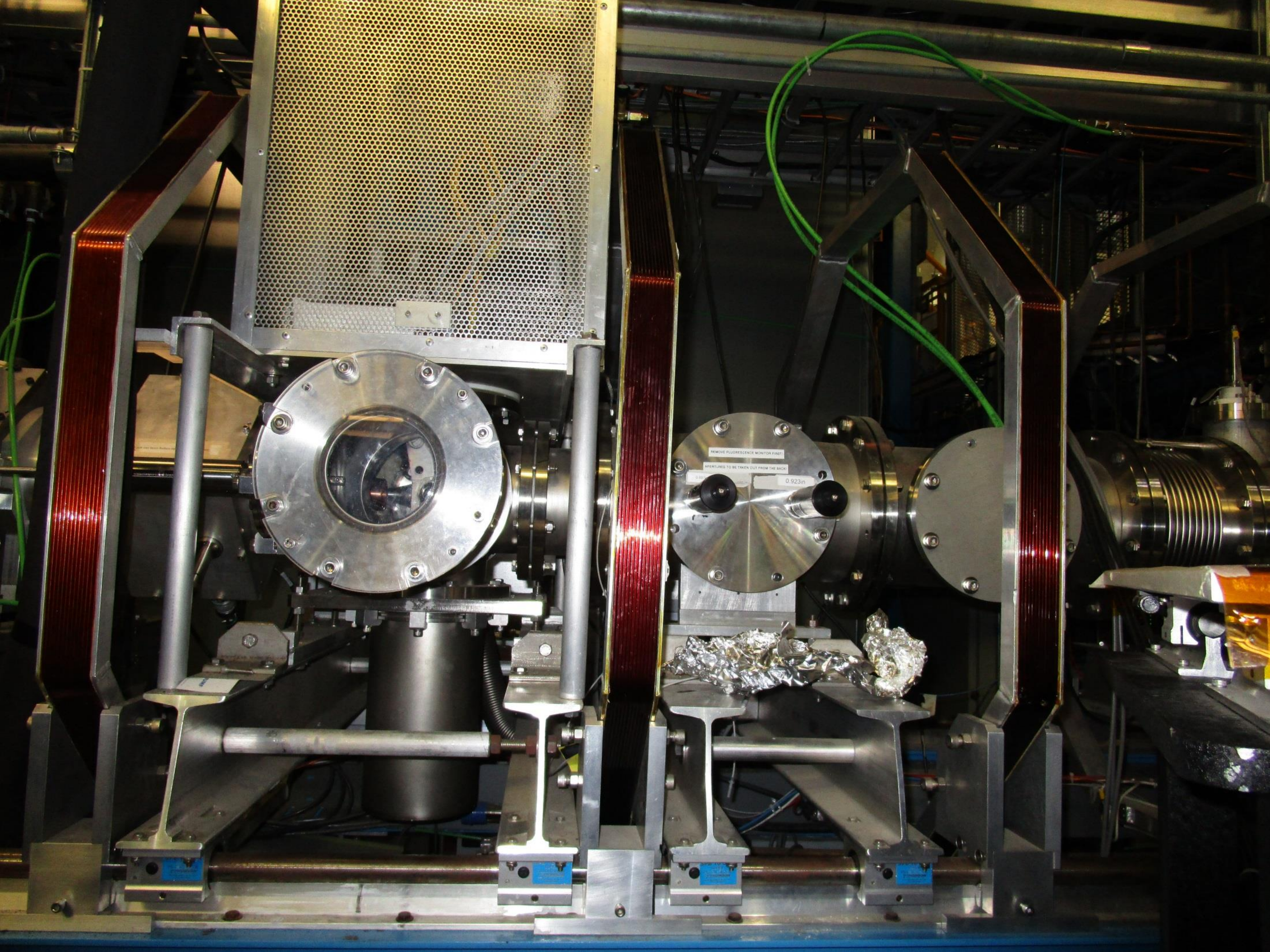


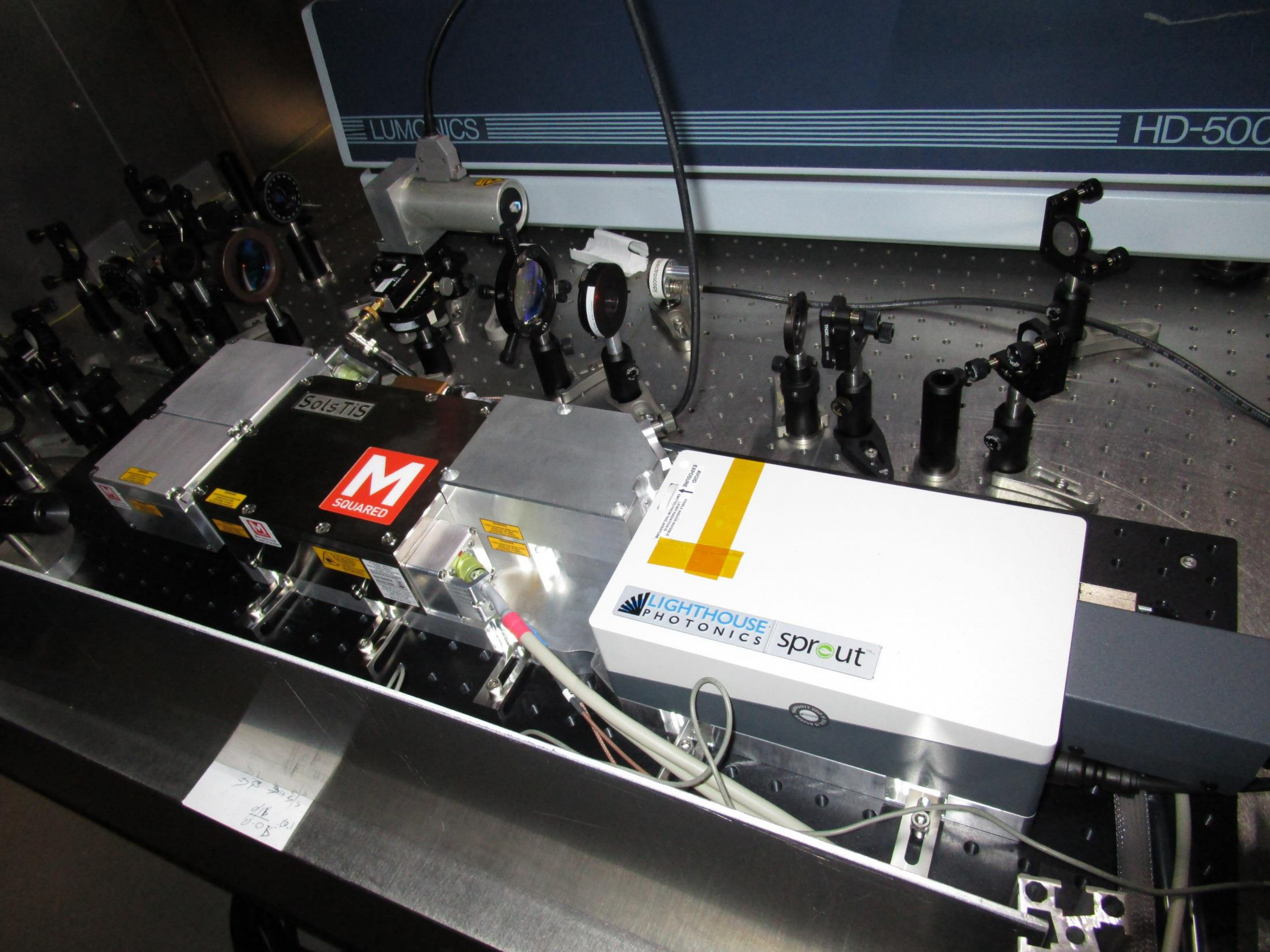
Noise Reduction = $\frac{\text{Bunched Noise}}{\text{DC Noise}}$ = $\frac{\text{Pulse duration}}{\text{Time between pulses}}$

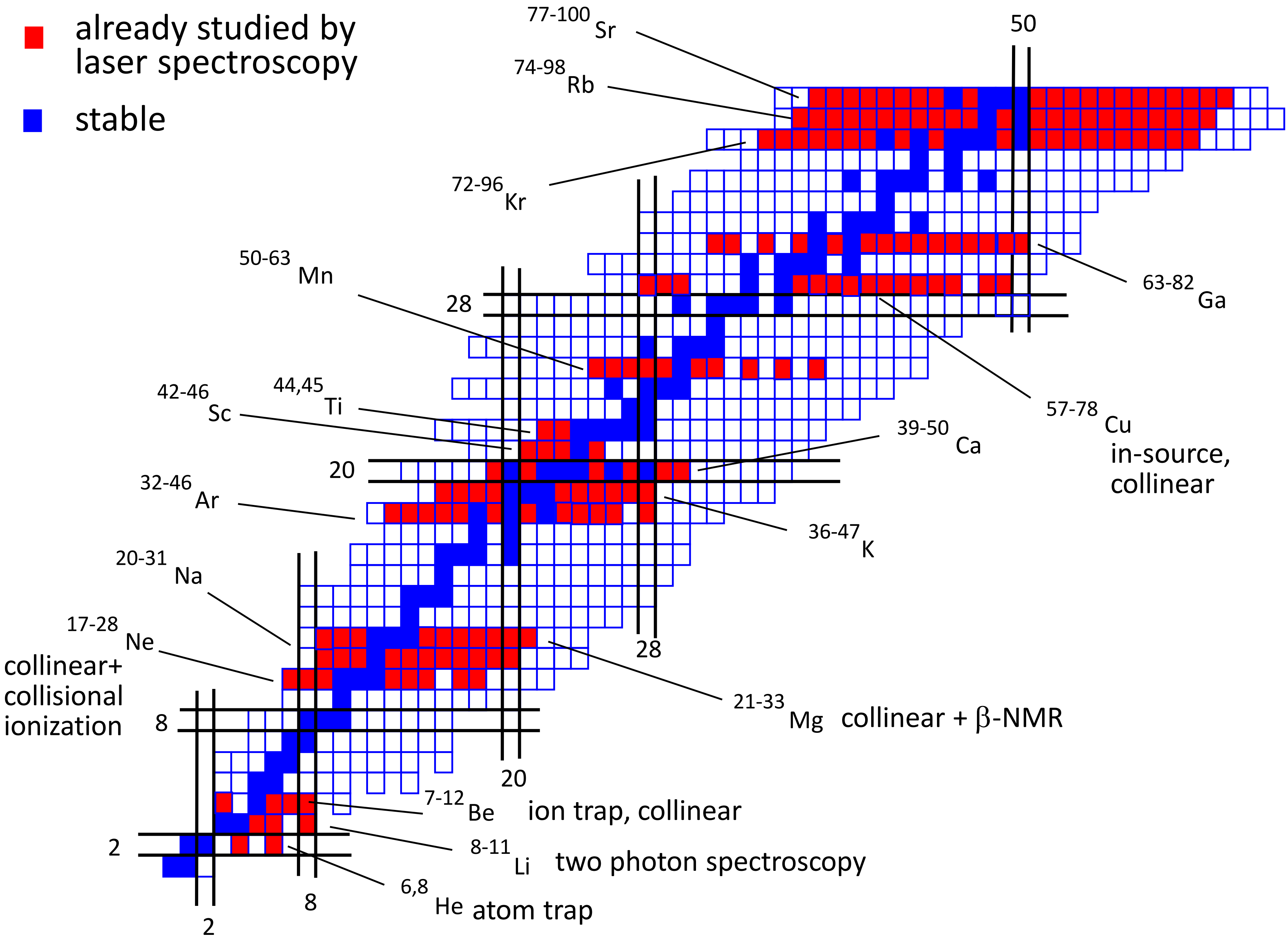
$$\frac{\Delta t}{T} \cong \frac{5\ \mu s}{50\ \mathrm{ms}} = 10^{-4}$$

Required beam intensity $\approx 10^{2}$ atoms/s

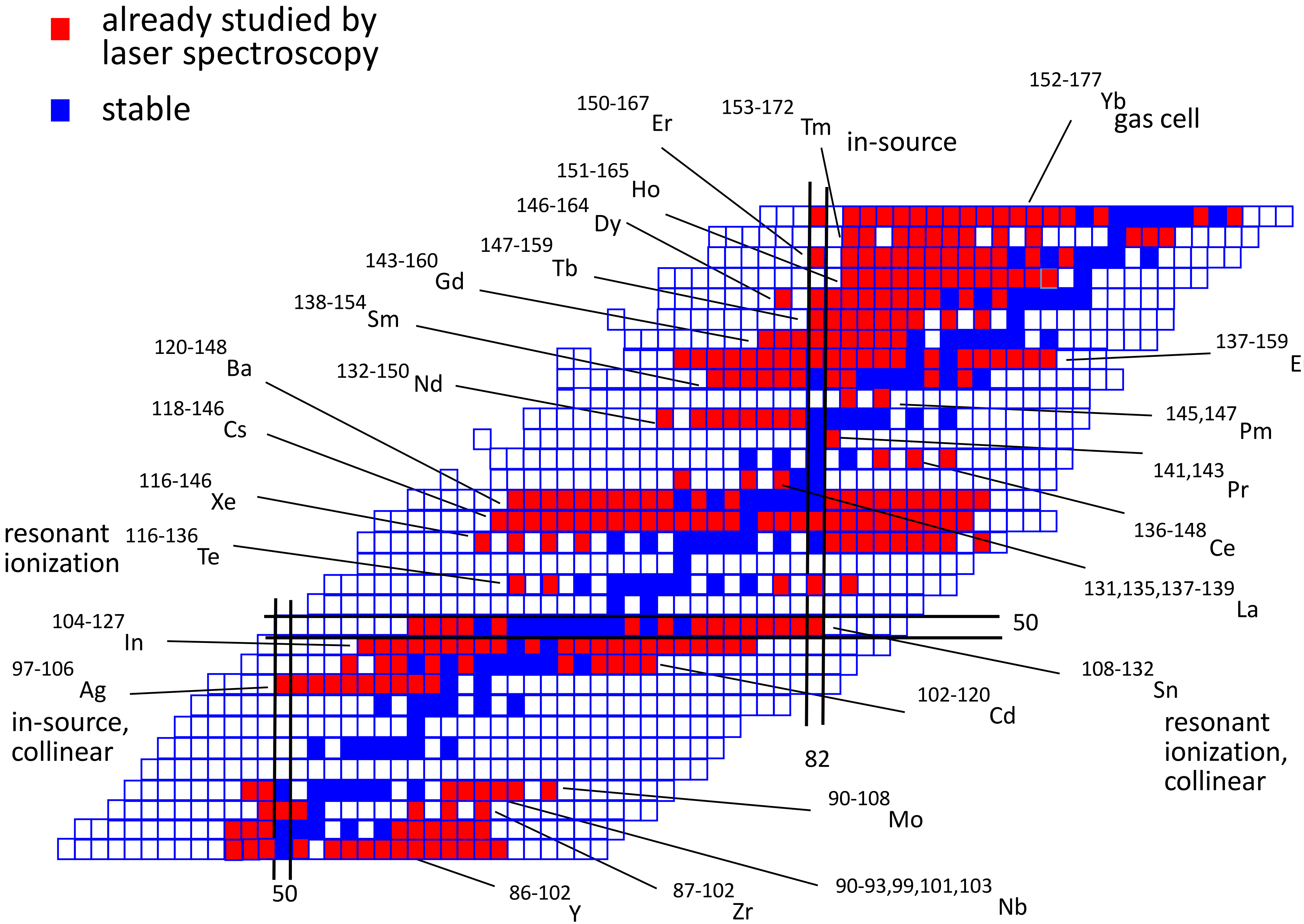

DANGER
HIGH VOLTAGE
Yield Station
measures production yields of nuclei produced at ISAC
CFBS
determines nuclear charge radii by precision laser spectroscopy
ISAC-I

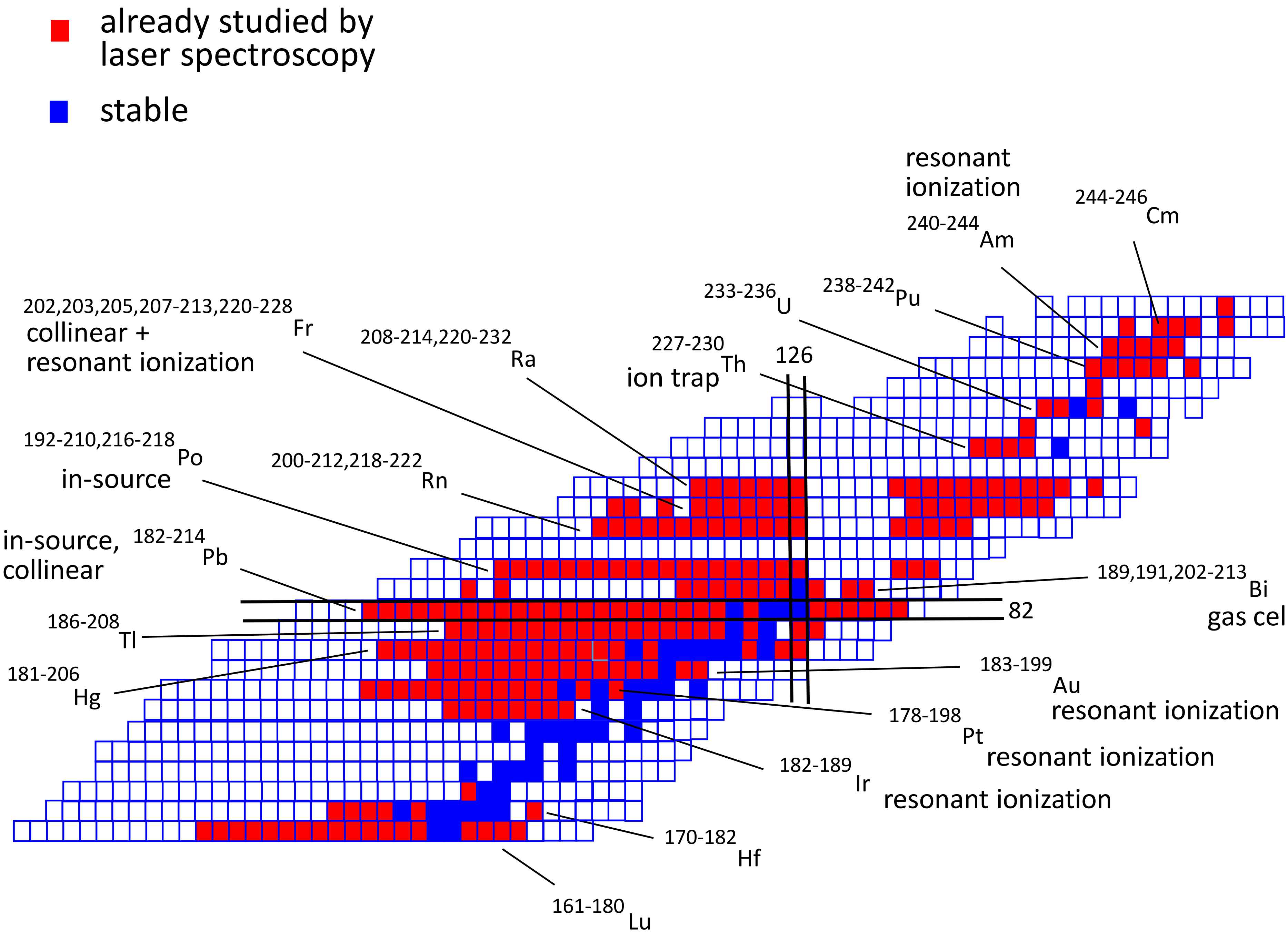

REMOVE FLUORESCENCE MONITOR FIRST!
APERTURES TO BE TAKEN OUT FROM THE BACK!
0.923in

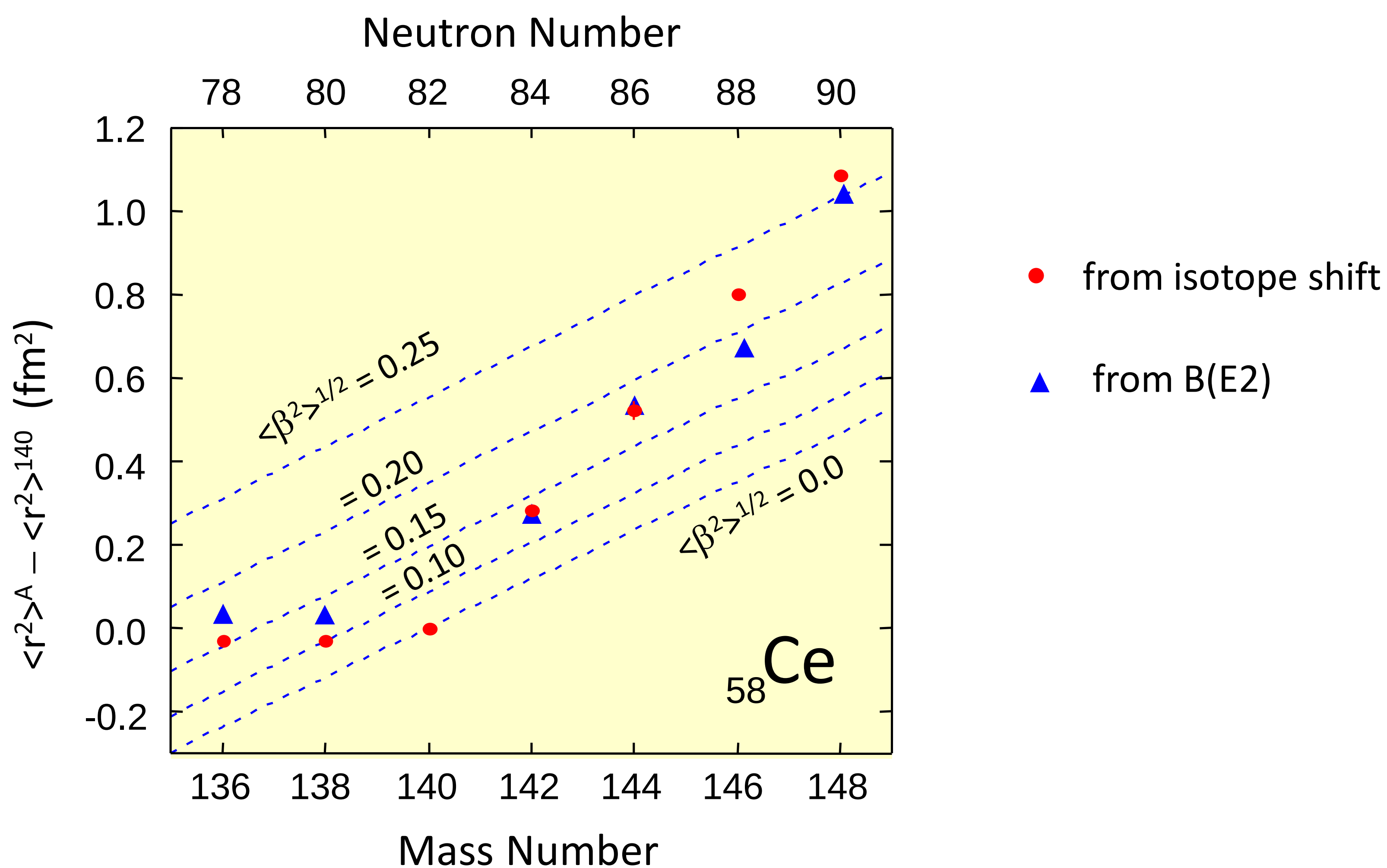

LUMONICS
HD-500
SolsTiS
M SQUARED
LIGHTHOUSE PHOTONICS
sprout



already studied by laser spectroscopy
stable
77-100 Sr
74-98 Rb
72-96 Kr
50
63-82 Ga
50-63 Mn
28
57-78 Cu
in-source, collinear
42-46 Sc
44,45 Ti
39-50 Ca
20
32-46 Ar
36-47 K
20-31 Na
17-28 Ne
collinear+ collisional ionization
28
21-33 Mg collinear + β-NMR
8
20
7-12 Be ion trap, collinear
2
8-11 Li two photon spectroscopy
6,8 He atom trap
8
2


already studied by laser spectroscopy
stable
152-177 Yb
gas cell
150-167 Er
153-172 Tm
in-source
151-165 Ho
146-164 Dy
147-159 Tb
143-160 Gd
138-154 Sm
137-159 Eu
120-148 Ba
132-150 Nd
145,147 Pm
118-146 Cs
141,143 Pr
116-146 Xe
136-148 Ce
resonant ionization
116-136 Te
131,135,137-139 La
50
104-127 In
108-132 Sn
97-106 Ag
102-120 Cd
in-source, collinear
82
resonant ionization, collinear
90-108 Mo
50
86-102 Y
87-102 Zr
90-93,99,101,103 Nb


already studied by laser spectroscopy
stable
resonant ionization
244-246 Cm
240-244 Am
238-242 Pu
233-236 U
202,203,205,207-213,220-228 Fr
collinear + resonant ionization
208-214,220-232 Ra
227-230 Th
ion trap
126
192-210,216-218 Po
in-source
200-212,218-222 Rn
in-source, collinear
182-214 Pb
189,191,202-213 Bi
82
gas cell
186-208 Tl
181-206 Hg
183-199 Au
resonant ionization
178-198 Pt
resonant ionization
182-189 Ir
resonant ionization
170-182 Hf
161-180 Lu



Neutron Number
78
80
82
84
86
88
90
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
136
138
140
142
144
146
148
Mass Number
$\langle r^2\rangle^A - \langle r^2\rangle^{140}$ (fm^2)
$\langle\beta^2\rangle^{1/2} = 0.25$
$= 0.20$
$= 0.15$
$= 0.10$
$\langle\beta^2\rangle^{1/2} = 0.0$
$_{58}$Ce
from isotope shift
from B(E2)

Liquid drop model

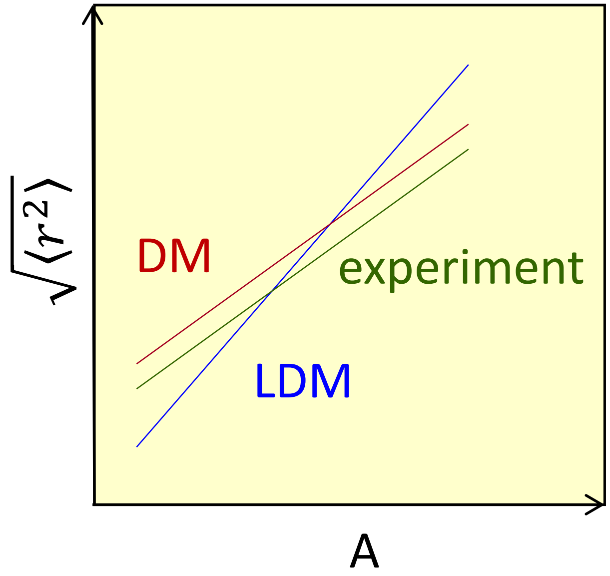
$$r^2 = \frac{3}{5} r_0^2 A^{\frac{2}{3}} \left(1 + \frac{5}{4\pi} \beta_2^2\right)$$

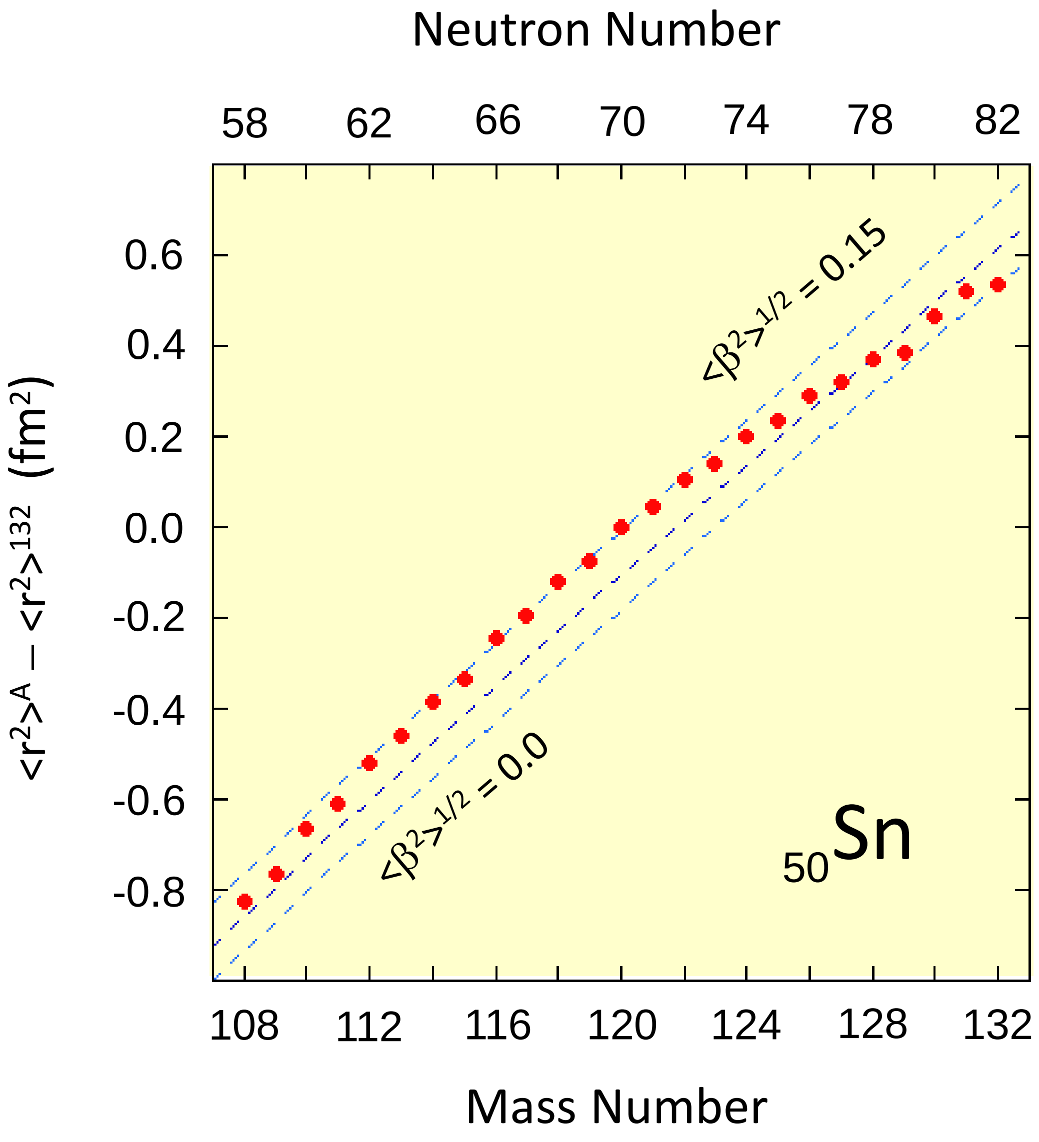
Droplet model

$$r^2 = \frac{3}{5} R_Z^2 A^{\frac{2}{3}} \left(1 + \frac{5}{4\pi} \beta_2^2\right)$$

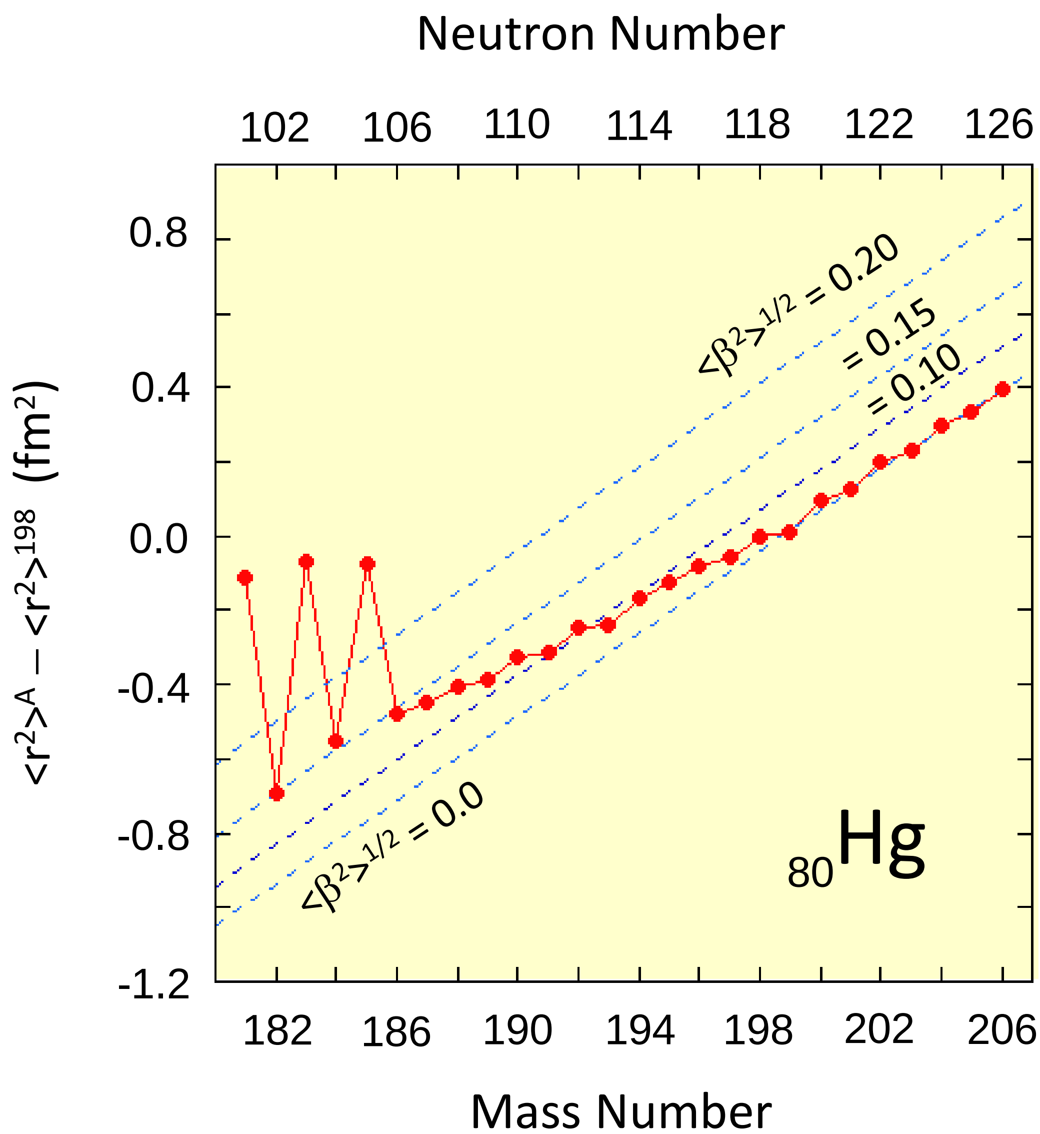
$$R_Z = r_0 A^{\frac{1}{3}} (1 + \bar{\varepsilon}) \times \left(1 - \frac{2N}{3A} \frac{I - \bar{\delta}}{B_S}\right)$$

$$I = \frac{N - Z}{A}$$



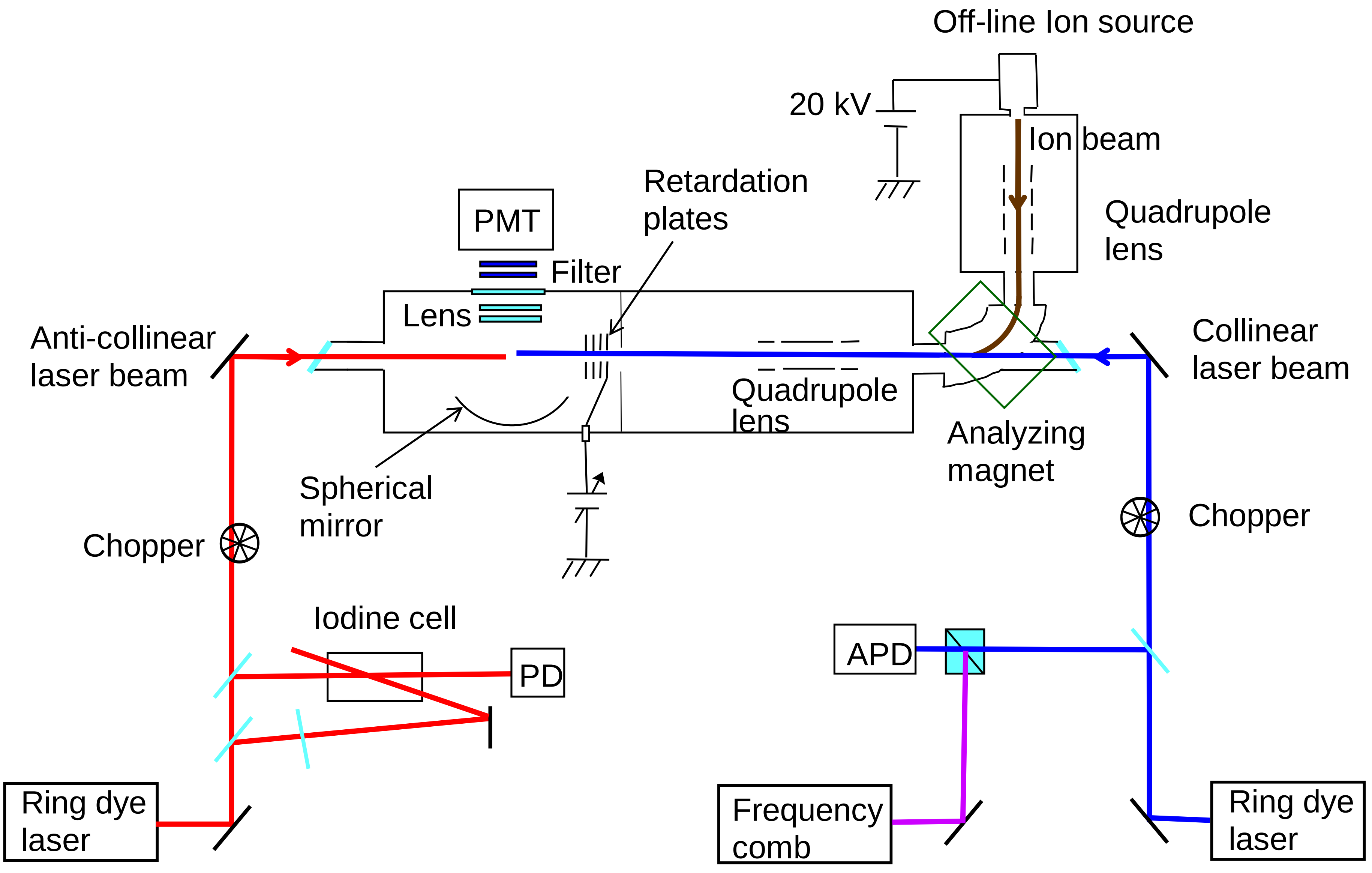


Neutron Number
58
62
66
70
74
78
82
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$\langle r^2\rangle^A - \langle r^2\rangle^{132}$ (fm^2)
$\langle\beta^2\rangle^{1/2} = 0.15$
$\langle\beta^2\rangle^{1/2} = 0.0$
$_{50}$Sn
108
112
116
120
124
128
132
Mass Number



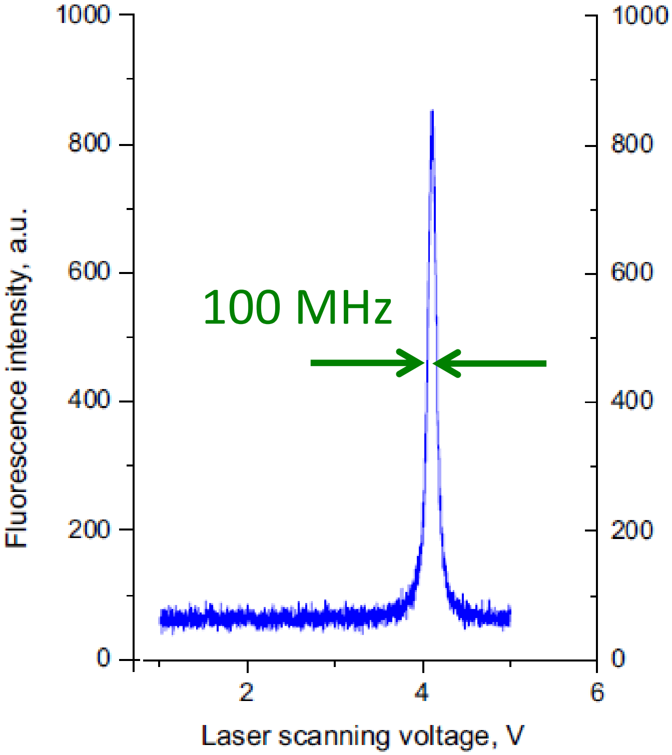
Neutron Number
102
106
110
114
118
122
126
0.8
0.4
0.0
-0.4
-0.8
-1.2
<r²>^A − <r²>^198 (fm²)
<β²>^1/2 = 0.20
= 0.15
= 0.10
<β²>^1/2 = 0.0
80Hg
182
186
190
194
198
202
206
Mass Number

Collinear laser spectroscopy setup at RIKEN

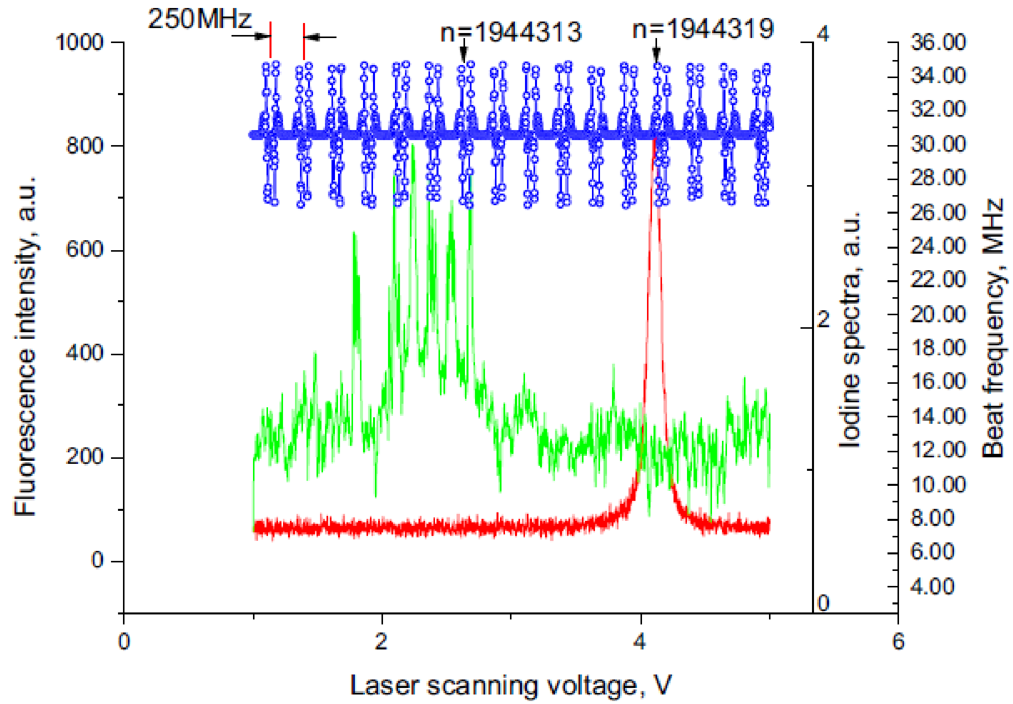


^{40}Ar

collinear



anti-collinear

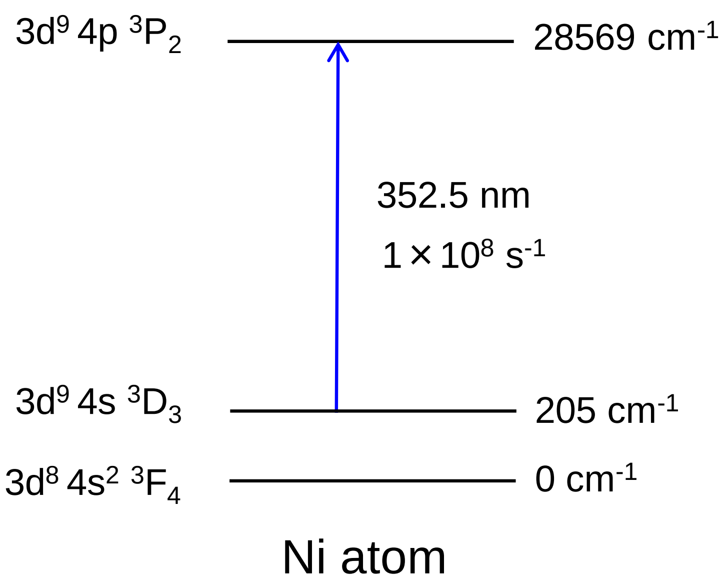


$$\nu_{\text{col}} = \nu_0 \sqrt{\frac{1+\beta}{1-\beta}} \qquad \beta = \frac{v}{c} \qquad \nu_{\text{anticol}} = \nu_0 \sqrt{\frac{1-\beta}{1+\beta}}$$

$$\nu_0 = (\nu_{\text{anticol}} \times \nu_{\text{anticol}})^{1/2}$$

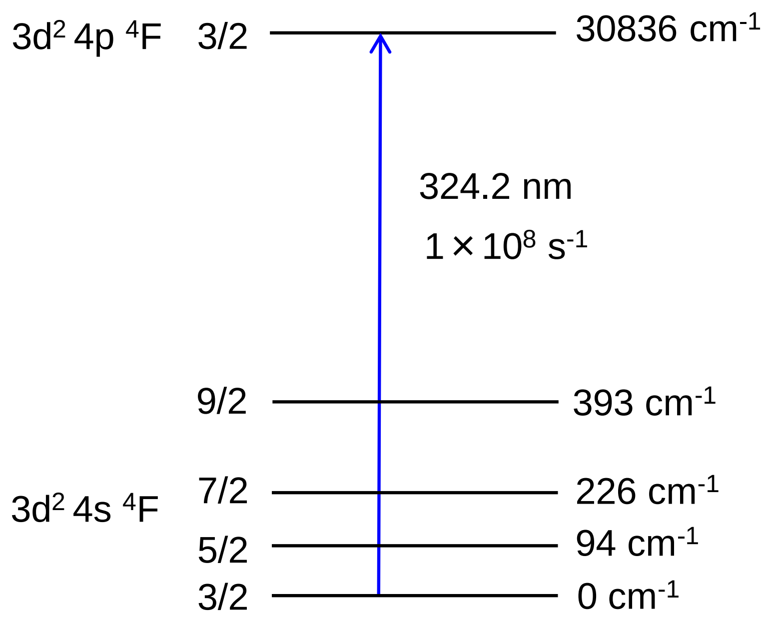
ν_0 = 485573619.7 (3) MHz

Ni (Z=28)



A	N	Half life	Expected yield @SLOWRI (ions/s)
54	26	110 ms	10^2
56	28	6.1 d	10^4
58	30	stable	
60	32	stable	
62	34	stable	
64	36	stable	
66	38	2.3 d	10^4
68	40	29 s	10^3
70	42	6.0 s	10^2
72	44	1.6 s	10^1
74	46	680 ms	10^0
76	48	240 ms	10^-2

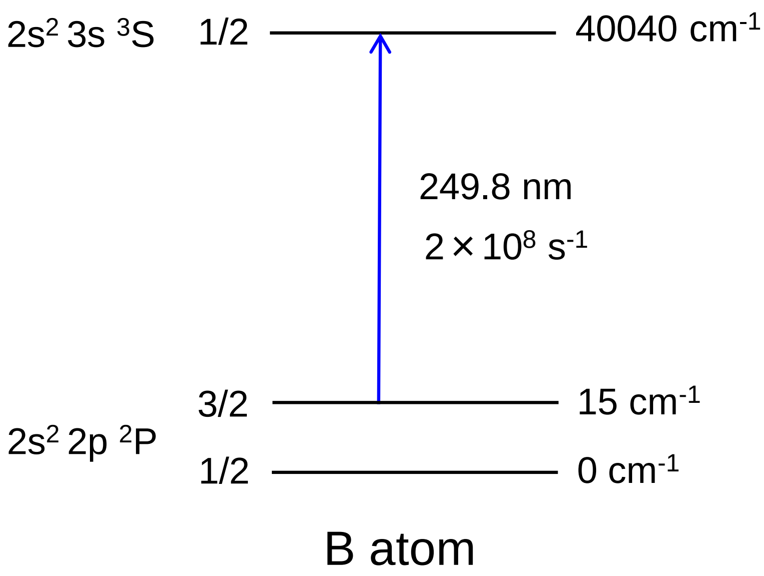
Ti (Z=22)



Ti ion

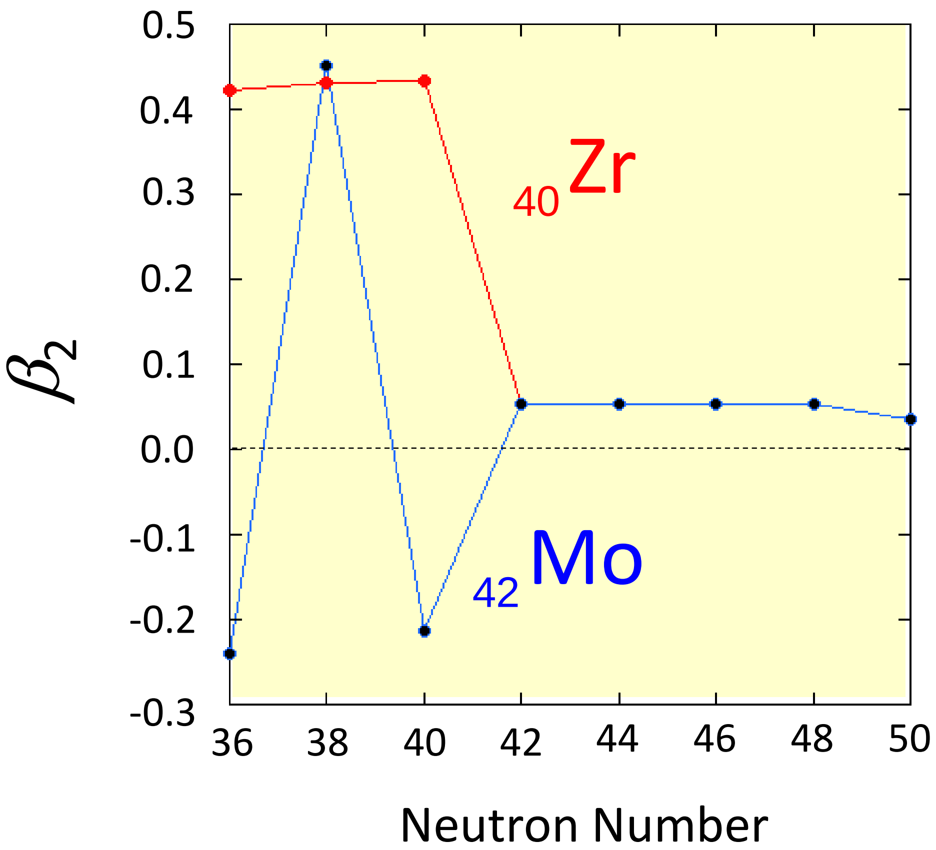
A	N	Half life	Expected yield @SLOWRI (ions/s)
42	20	200 ms	10^2
44	22	59 y	10^4
46	24	stable	
48	26	stable	
50	28	stable	
52	30	1.7 m	10^4
54	32	2.0 s	10^2
56	34	200 ms	10^1

B (Z=5)



A	N	Half life	Expected yield @SLOWRI (ions/s)
8	3	770 ms	
9	4	10^-18 s	
10	5	stable	
11	6	stable	
12	7	20 ms	
13	8	17 ms	
14	9	13 ms	
15	10	10 ms	

Zr (Z=40)

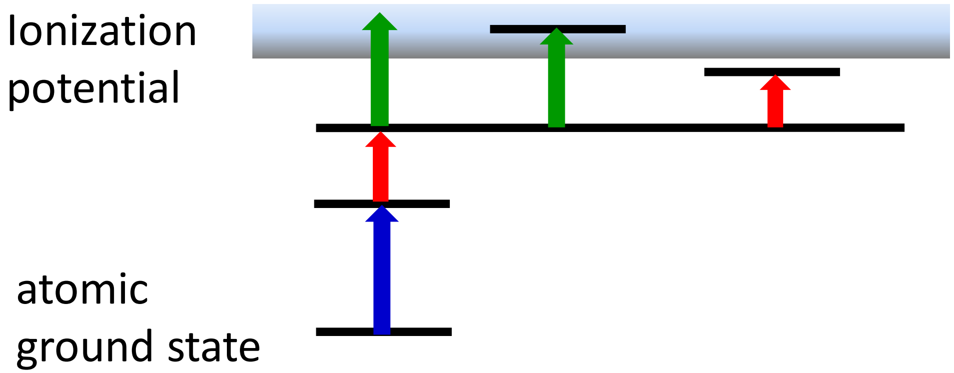


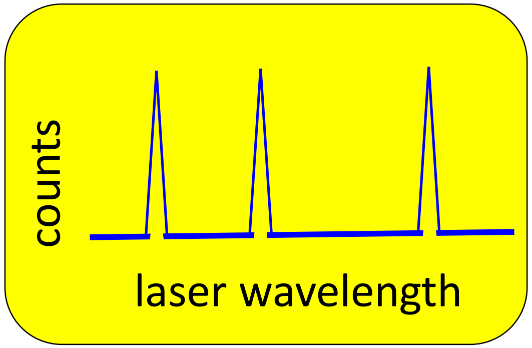
FRDM prediction by Möller

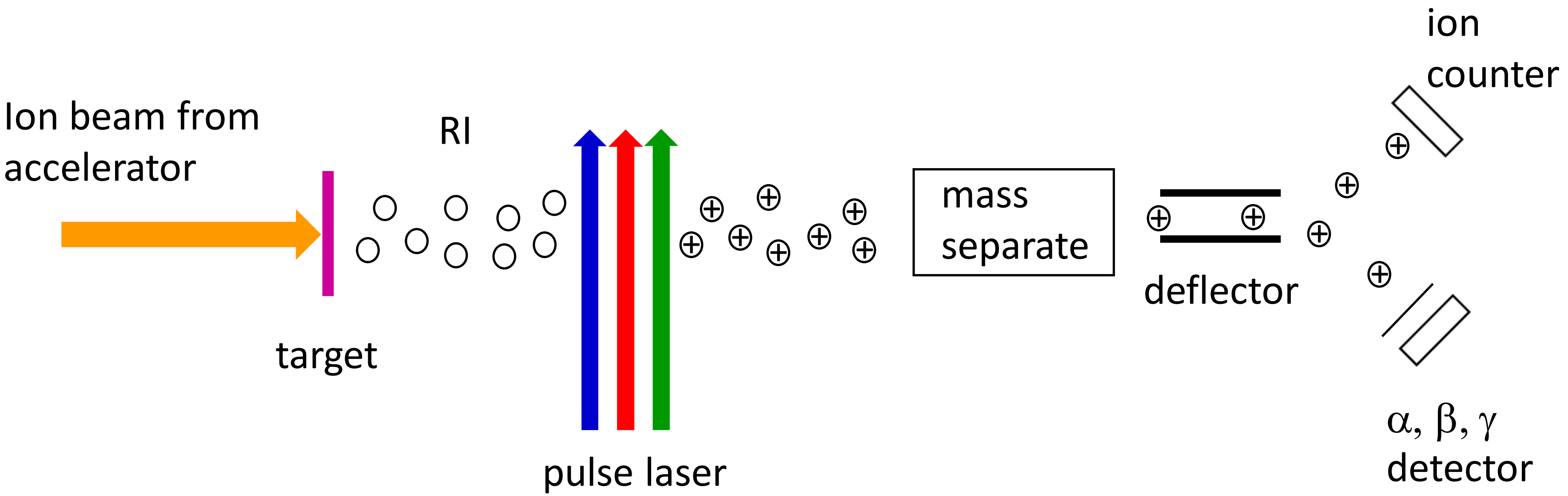
A	N	Half life	Expected yield @SLOWRI (ions/s)
80	40	4.6 s	10^2
81	41	5.5 s	3×10^3
82	42	32 s	9×10^4
83	43	42 s	10^6
84	44	26 m	8×10^6
85	45	11 m	3×10^7
86	46	17 h	8×10^7
87	47	1.7 h	10^8

^{124}Xe 500 pnA

Laser spectroscopy with resonant ionization laser-ion-source





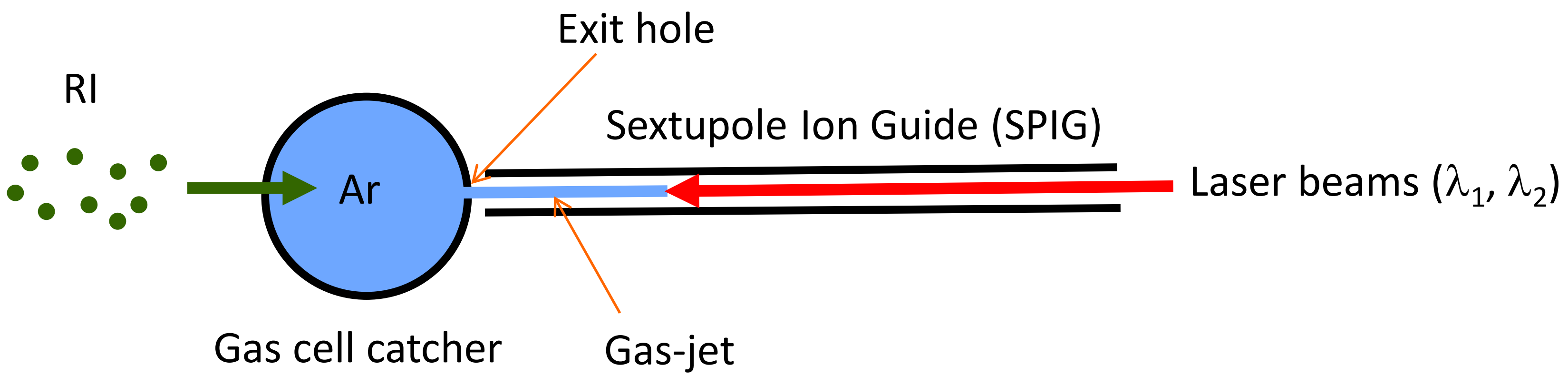


Methods of laser spectroscopy with laser-ion-source

- In-source laser spectroscopy: ISOLDE (Cu, Po), PNPI (Yb, Tm)
- In-gas-cell laser spectroscopy: Leuven (Cu, Ag)

  Line width ~ 6 GHz (laser bandwidth ~ 2 GHz)

- In-gas-jet laser spectroscopy planned at PALIS (SLOWRI)



Line width ~ 3 GHz (laser bandwidth ~ 2 GHz),

~ 0.5 GHz (narrowband laser bandwidth ~ 20 MHz)

Collinear laser spectroscopy

- sensitivity 100 atoms/s
- resolution 100 MHz

In-gas jet laser spectroscopy

- sensitivity 0.1 atoms/s
- resolution 500 MHz (with narrowband laser)

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TRIUMF	M. Pearson