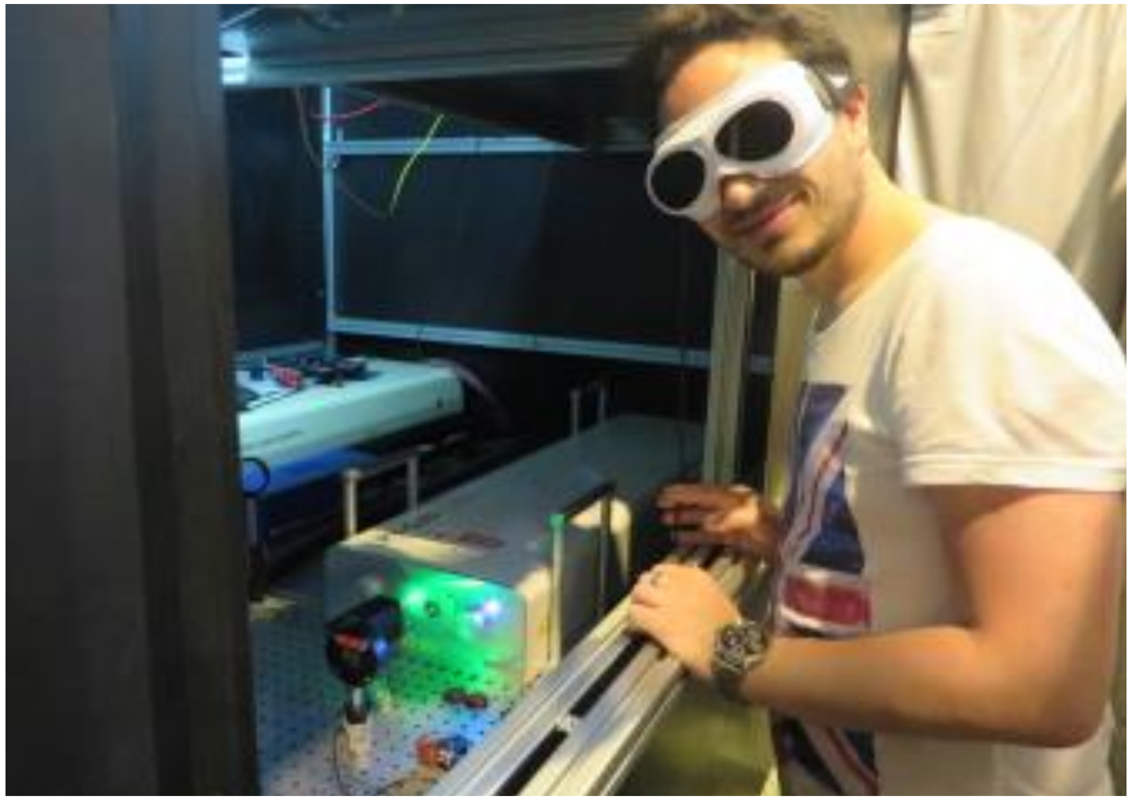
MANCHESTER
1824

Laser-assisted modern nuclear physics

Lecture 1:
From the atom to the nucleus
& the production of radioactive ion beams

Dr Thomas Elias Cocolios
STFC Ernest Rutherford Research Fellow
The University of Manchester, UK



Who is Dr Thomas?

French - Greek - American

B.Sc.'03, M.Sc.'05, McGill University, Montréal, Qc

Ph.D.'10, KU Leuven, Belgium

CERN Research Fellow 2010-12, Geneva, CH

STFC Ernest Rutherford Research Fellow 2012-15, Manchester, UK

Who is Dr Thomas?

<u>Keywords</u>

Laser

Polonium

Out of the box

Knitting

Singing

Running

Laser-assisted modern nuclear physics

- Lecture 1:
    - Fundamentals of the atom-nucleus interaction
    - Lasers for the production of radioactive ion beams
- Lecture 2:
    - High-resolution collinear laser spectroscopy
    - Atom trapping
    - Anti-atomic studies

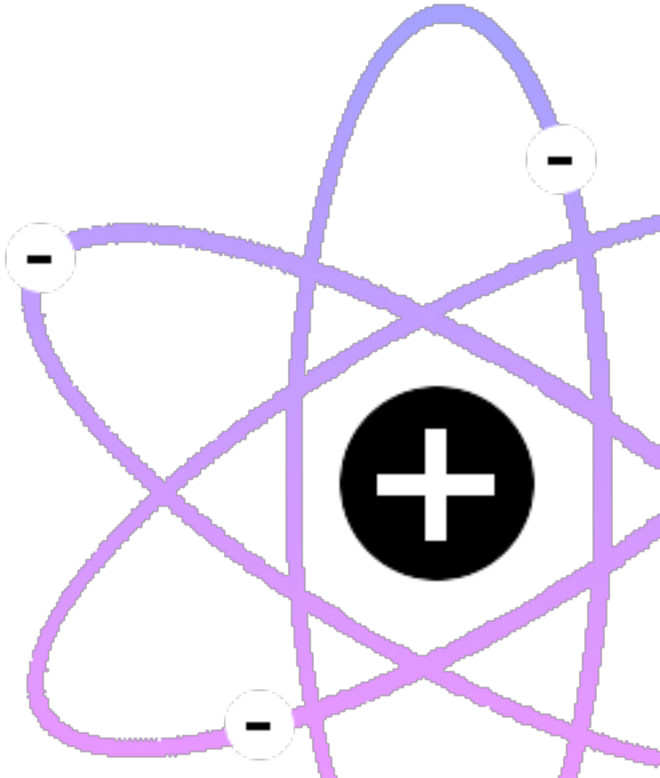
The atom

A quantum system under EM forces

$$\left(- \frac{\hbar}{2m} \nabla^2 + V \right) \psi = E\psi.$$

$$V(r) = \frac{Ze^2}{4\pi\epsilon_0 r}$$

Let’s enjoy some math now!



Solving the (hydrogen) atom

Double separation of variables in spherical coordinates

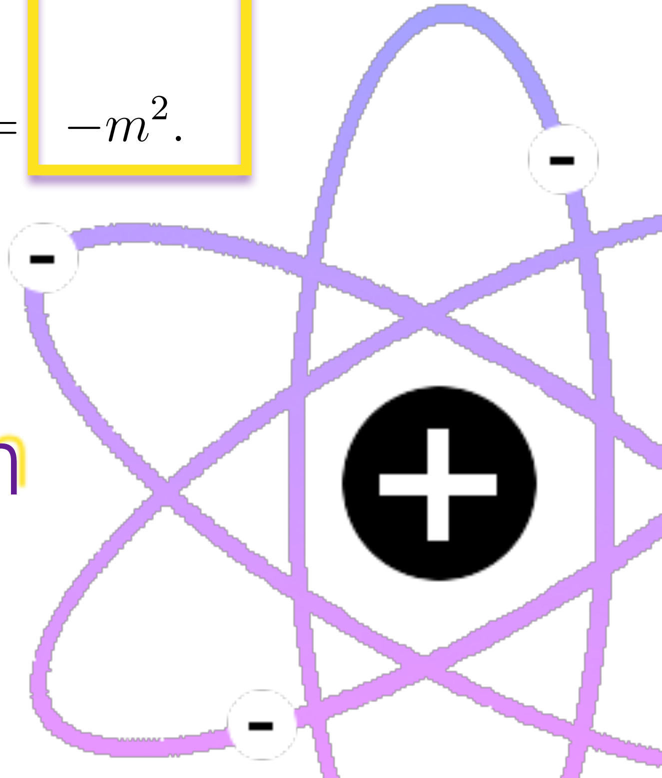
$$\boxed{\psi(r,\theta,\phi) = R(r)Y(\theta,\phi)}$$

$$\begin{aligned}
\frac{1}{R(r)}\frac{d}{dr}\left(r^2\frac{d}{dr}\right)R(r) - \frac{2mr^2}{\hbar^2}\left[V(r)-E\right] &= \boxed{l(l+1),} \\
\frac{1}{Y(\theta,\phi)\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)Y(\theta,\phi) + \frac{1}{Y(\theta,\phi)\sin^2\theta}\frac{\partial^2}{\partial\phi^2}Y(\theta,\phi) &= \boxed{-l(l+1).}
\end{aligned}$$

$$\boxed{Y(\theta,\phi) = f(\theta)g(\phi)}$$

$$\begin{aligned}
\frac{\sin\theta}{f(\theta)}\frac{d}{d\theta}\left(\sin\theta\frac{d}{d\theta}\right)f(\theta) + l(l+1)\sin^2\theta &= \boxed{m^2 \quad \&} \\
\frac{1}{g(\phi)}\frac{d^2}{d\phi^2}g(\phi) &= \boxed{-m^2.}
\end{aligned}$$

Separation constants make angular momentum quantum numbers appear naturally



Solving the (hydrogen) atom

Solving backwards reveals some conditions on *l* & *m*

$$g_m(\phi) = e^{im\phi}$$

$$f_{l,m}(\theta) = (-1)^m \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} P_{l,m}(\cos\theta),$$

$$\text{where} \quad \boxed{l \in \mathbb{N}} \; \boxed{\& \quad |m| \le l.}$$

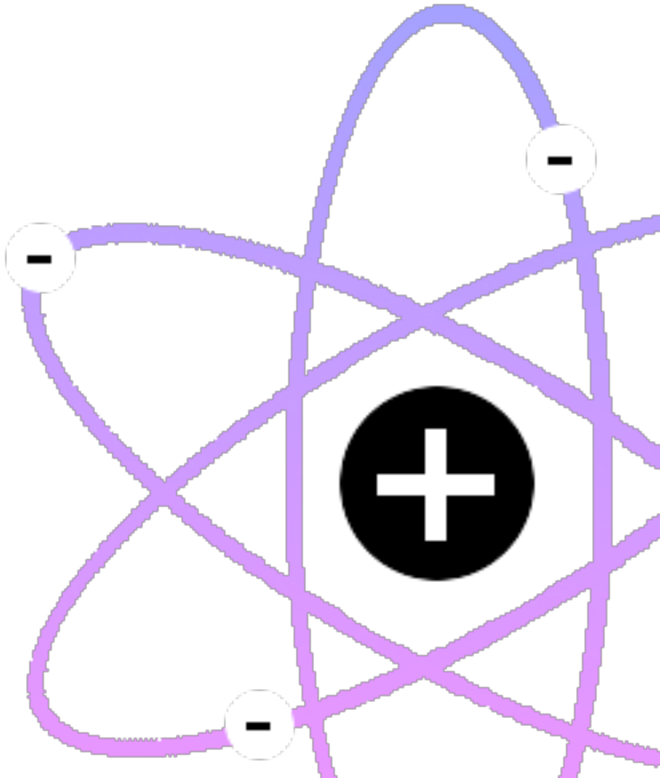
$$R_{n,l}(r) = \sqrt{{\frac{2}{na_0}}^{3} \frac{(n-l-1)!}{2n\big[(n+l)!\big]^3}} e^{-r/na_0} \left(\frac{2r}{na_0}\right)^l L^{2l+1}_{n-l-1}\left(\frac{2r}{na_0}\right),$$

$$\text{where} \quad \boxed{n \in \mathbb{N}} \; \boxed{\& \quad n \ge l+1}$$

And let us not forget the electron spin too!

$$j = l \pm \frac{1}{2}, \quad j > 0.$$

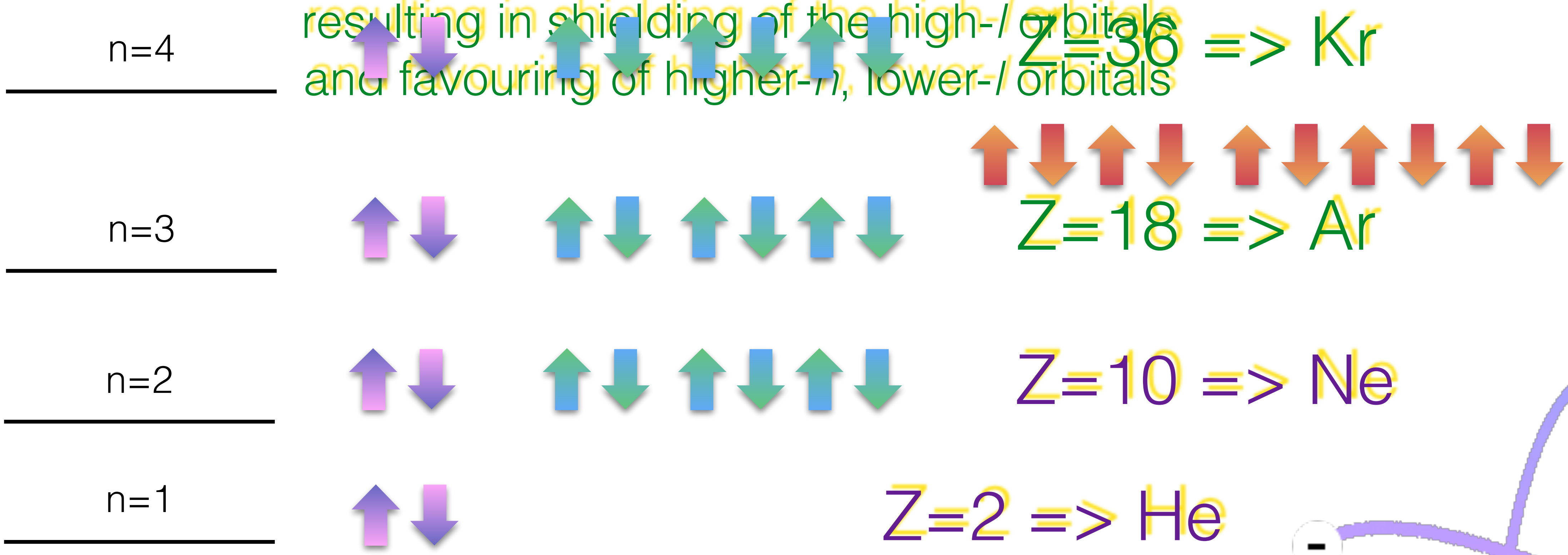
Quantisation is a natural outcome of solving the Schrödinger equation



Building up the atom

Ordering up the levels reveals some known pattern

Atoms are not hydrogen-like and the electrons interact with one another resulting in shielding of the high-*l* orbitals and favouring of higher-*n*, lower-*l* orbitals



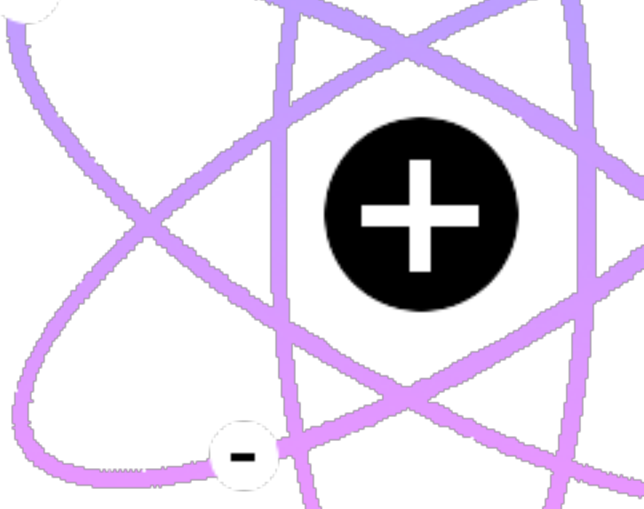
Z=36 => Kr

Z=18 => Ar

Z=10 => Ne

Z=2 => He

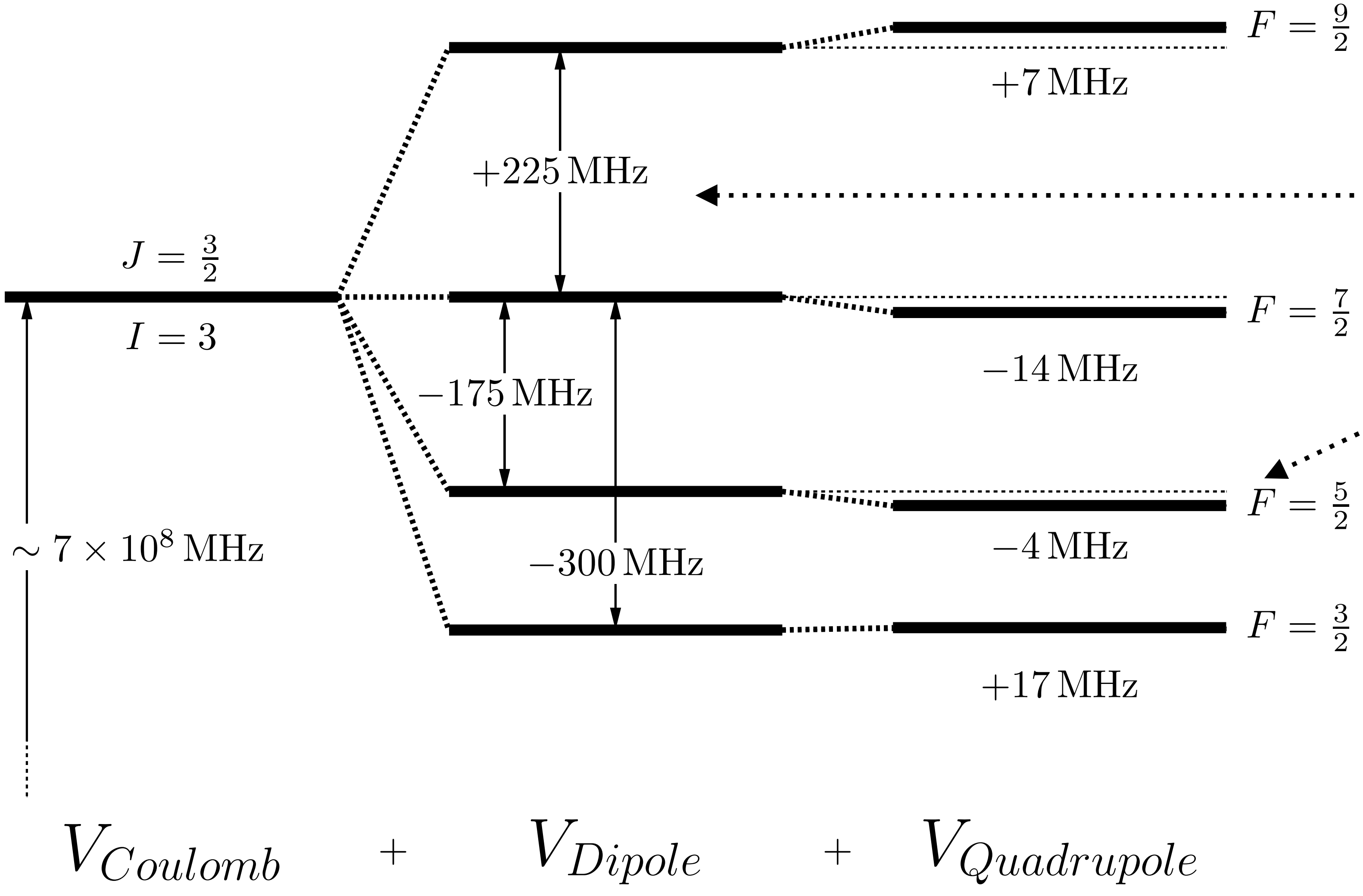
The natural appearance of atomic magic numbers



Taking a closer look

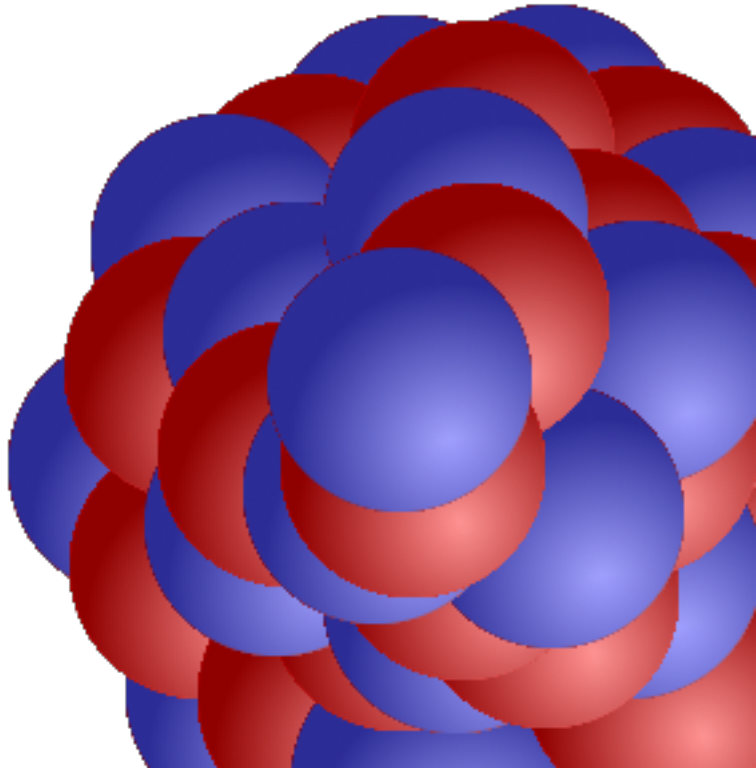
Hyperfine structure of the atomic levels

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J},$$
$$|I - J| \leq F \leq I + J.$$



ΔE ~ μ, Q

The nucleus is not a point charge!



Hyperfine structure

Let’s do the math!

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J},$$
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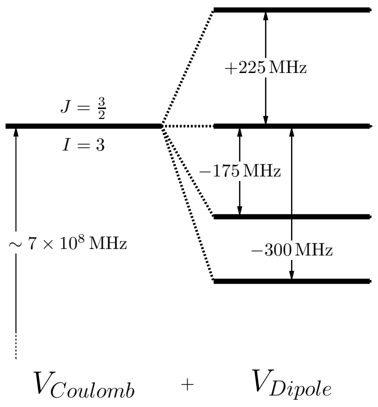


$$\Delta E = \frac{A}{2} K$$

$$A = \frac{\mu B_0}{IJ}$$

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

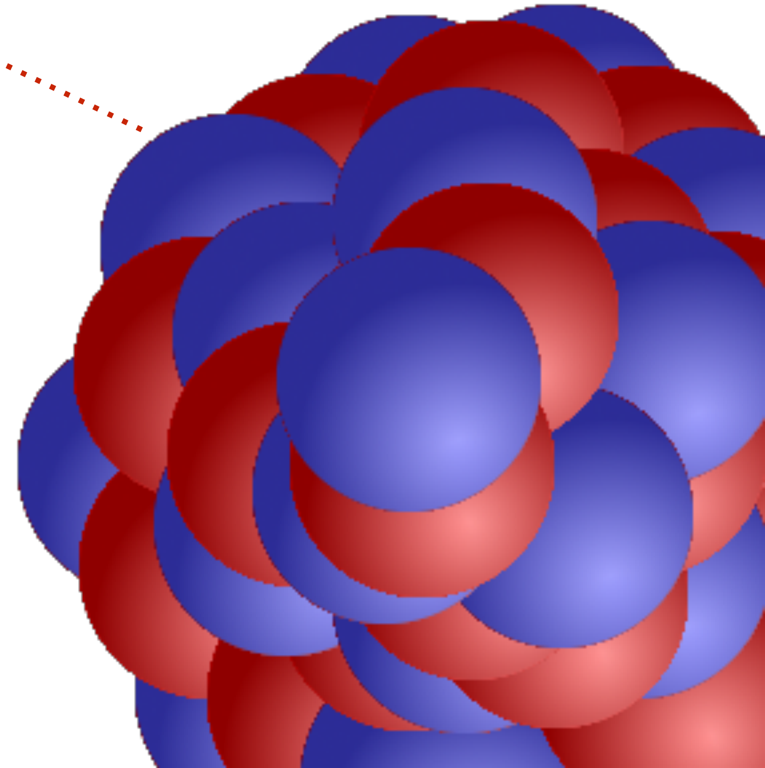
I,J > 0

Measuring the nuclear spin!

$$\frac{A_1}{A_2} = \frac{\mu B_{01}}{I J_1} \frac{I J_2}{\mu B_{02}} = \frac{B_{01} J_2}{B_{02} J_1},$$

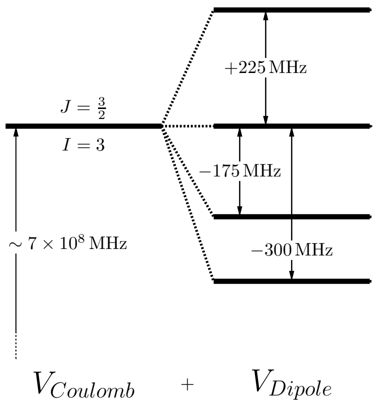
$$\frac{A}{A'} = \frac{\mu B_0}{IJ} \frac{I' J}{\mu' B_0} = \frac{\mu I'}{\mu' I}$$

Magnetic dipole moment



Hyperfine structure

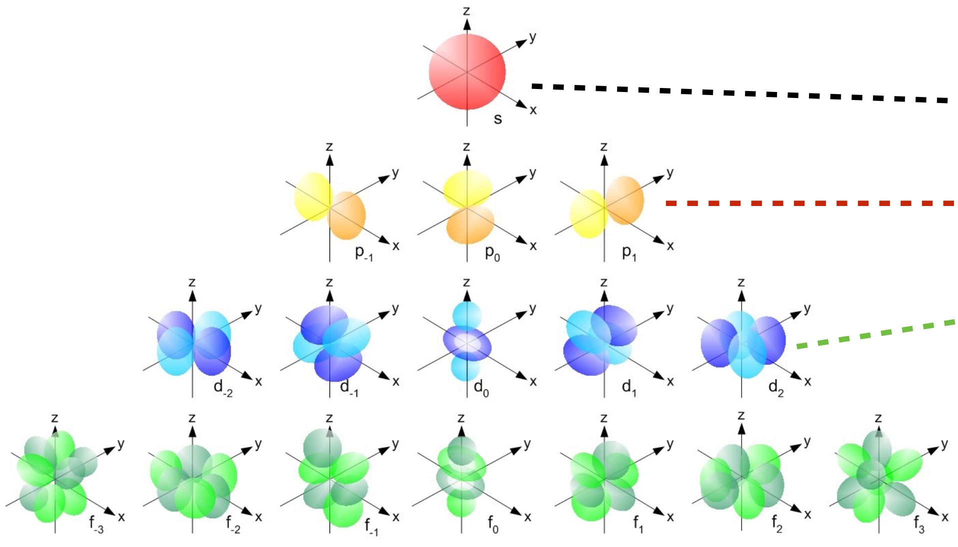
A perturbation of a perturbation of a perturbation of a pertu

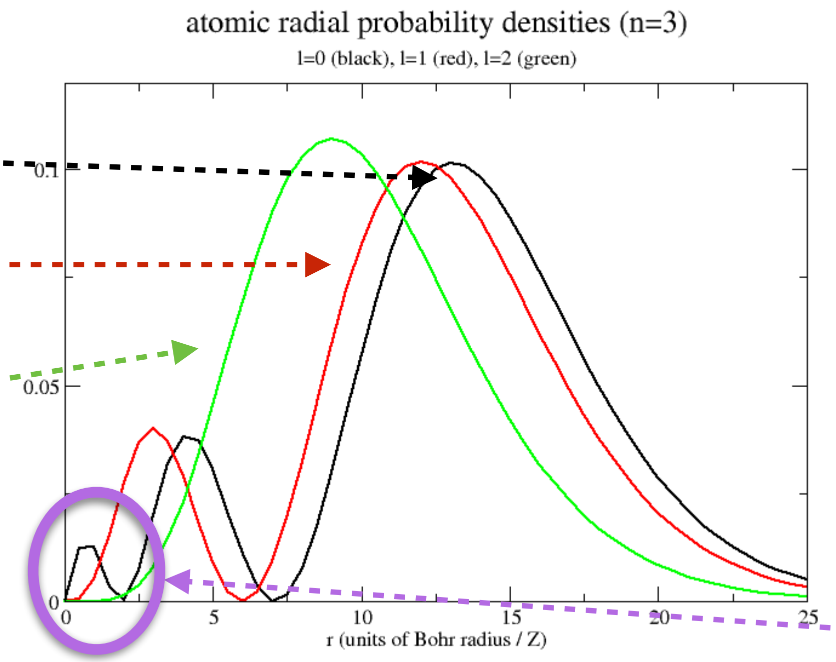


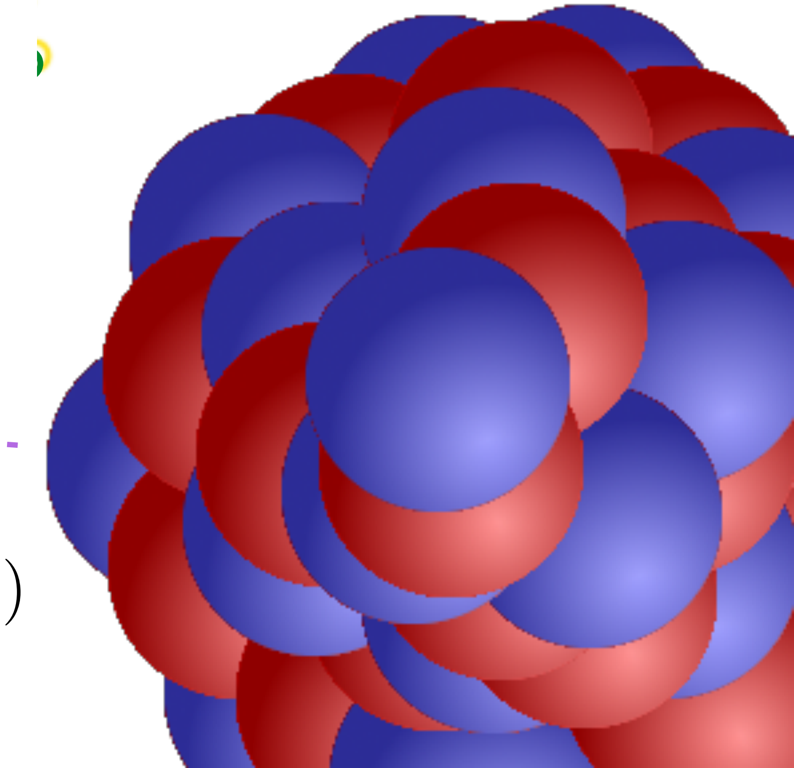
$$\Delta E = \frac{A}{2} K \qquad A = \frac{\mu B_0}{IJ}$$

For s and $p_{1/2}$ orbitals, B_0 is not uniform over the nuclear volume

Averaging the interaction over the volume induces a correction





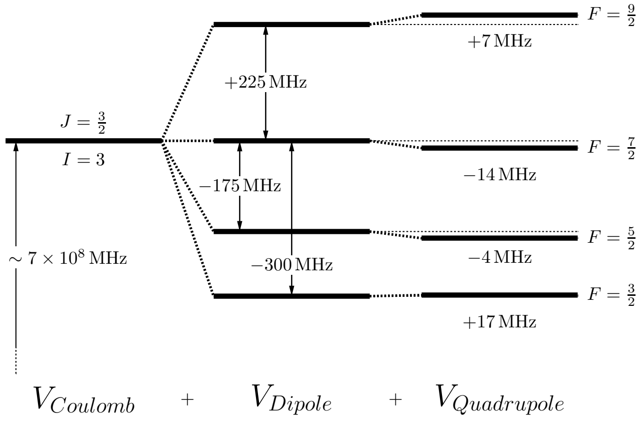


Hyperfine anomaly

$$\frac{A}{A'} = \frac{\mu I'}{\mu' I} \frac{1+\epsilon}{1+\epsilon'} \approx \frac{\mu I'}{\mu' I}(1+\Delta')$$

Hyperfine structure

Let's do the math!



$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J},$$

$$|I - J| \leq F \leq I + J.$$

$$\Delta E = \frac{B}{2} \frac{3K(K+1) - 2I(I+1)2J(J+1)}{2I(2I-1)2J(2J-1)}$$

$$B = \frac{eQ}{4} \frac{\partial^2 V}{\partial z^2}$$

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

I,J > 1/2

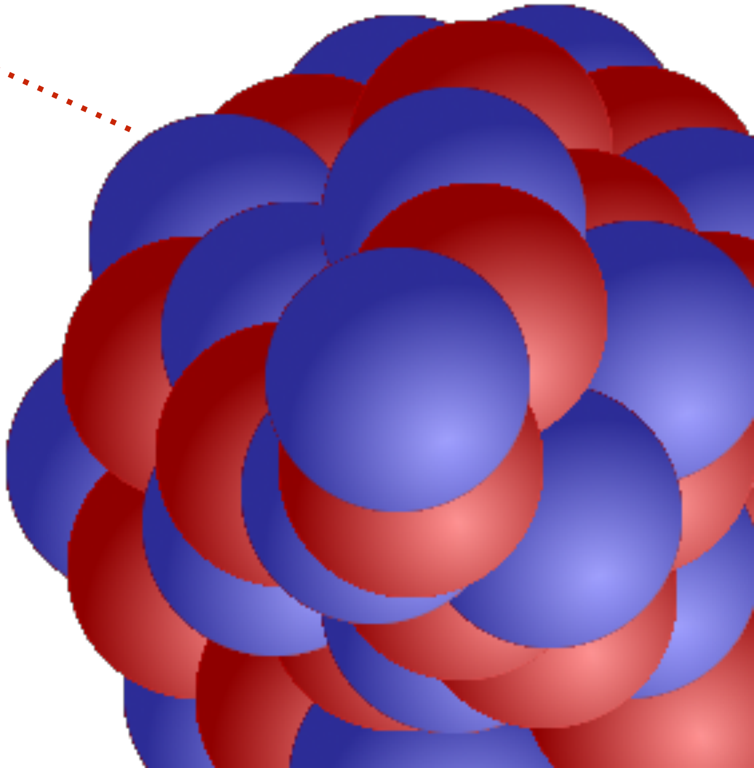
A perturbation

of a perturbation

of a perturbation

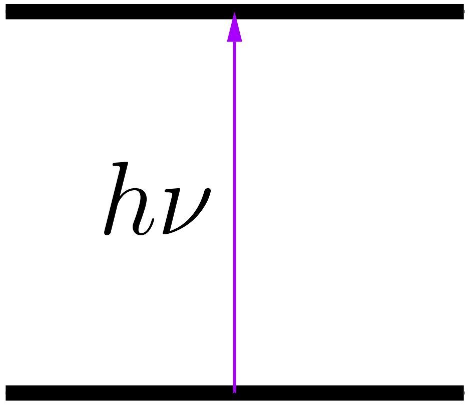
of a perturbation

Electric quadrupole moment



Atomic transitions

A question of intensity



$$-\frac{\mathrm{d}N_2}{\mathrm{d}t} = \frac{\mathrm{d}N_1}{\mathrm{d}t} = AN_2 - B_{12}\rho(\nu)N_1 + B_{21}\rho(\nu)N_2$$

spontaneous decay

absorption

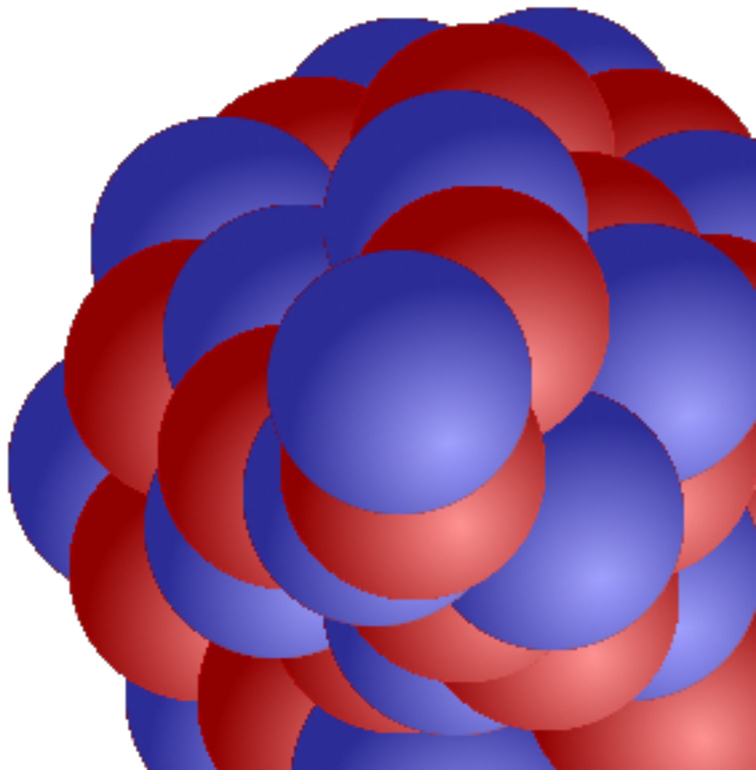
induced emission

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = -AN_2$$

inverse of the transition lifetime
i.e. partial lifetime

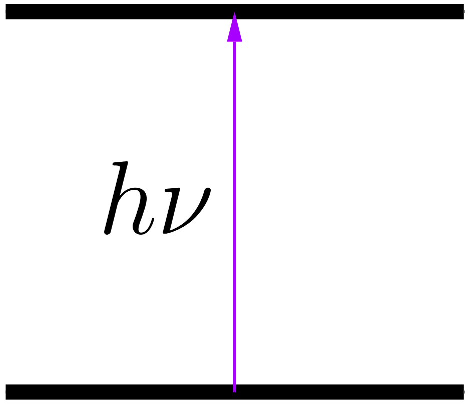
$$\tau = 1/\sum_i A_i$$

Einstein coefficients



Atomic transitions

What the atom may or may not do



To first order, the photon field can be considered as an electric dipole field (E1)

$$\begin{aligned} \Delta l &= \pm 1 \\ \Delta J &= 0, \pm 1, \quad J = 0 \nrightarrow 0 \\ \Delta F &= 0, \pm 1, \quad F = 0 \nrightarrow 0 \end{aligned}$$

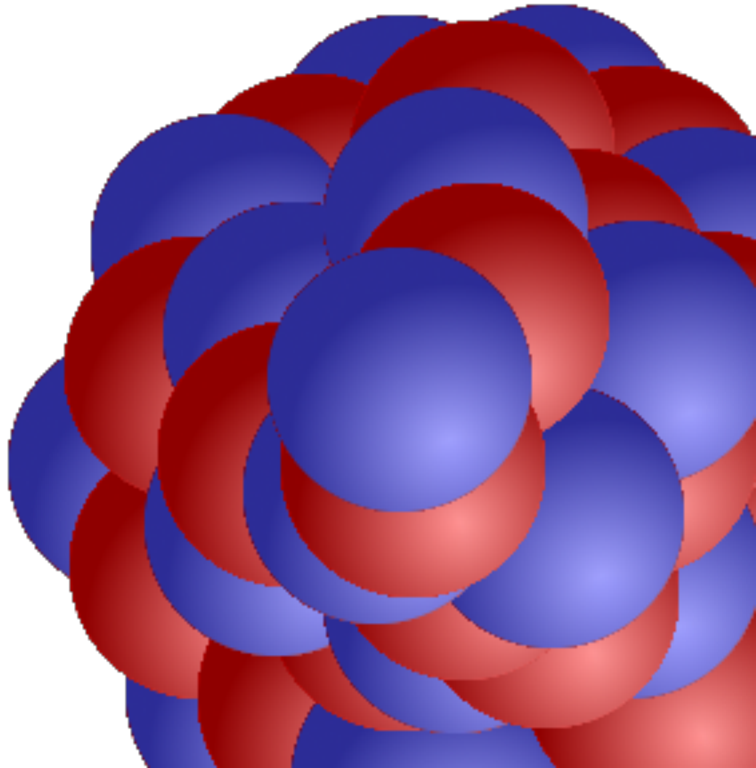
Parity change

1 unit of angular momentum

carried by the photon
=> triangular relation

Selection rules

$$s \leftrightarrow p,\ p \leftrightarrow d,\ d \leftrightarrow f,\ \ldots$$



Atomic transitions

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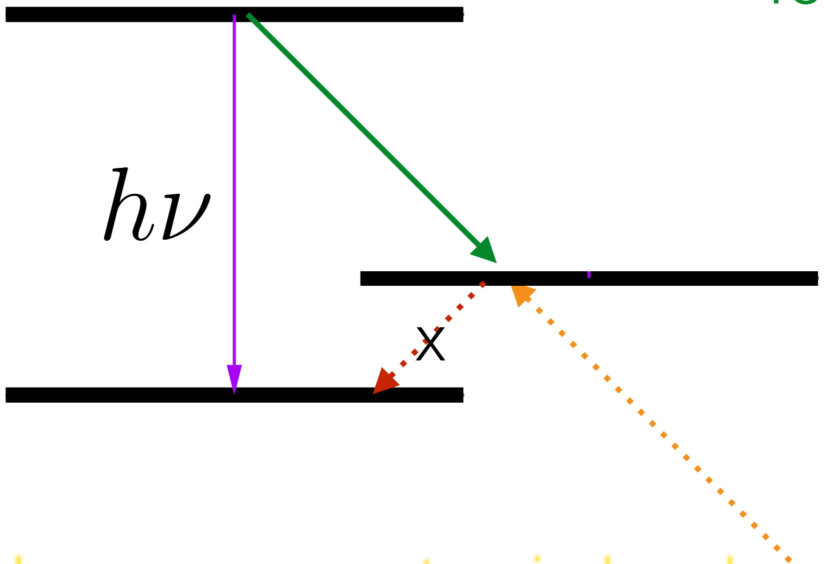

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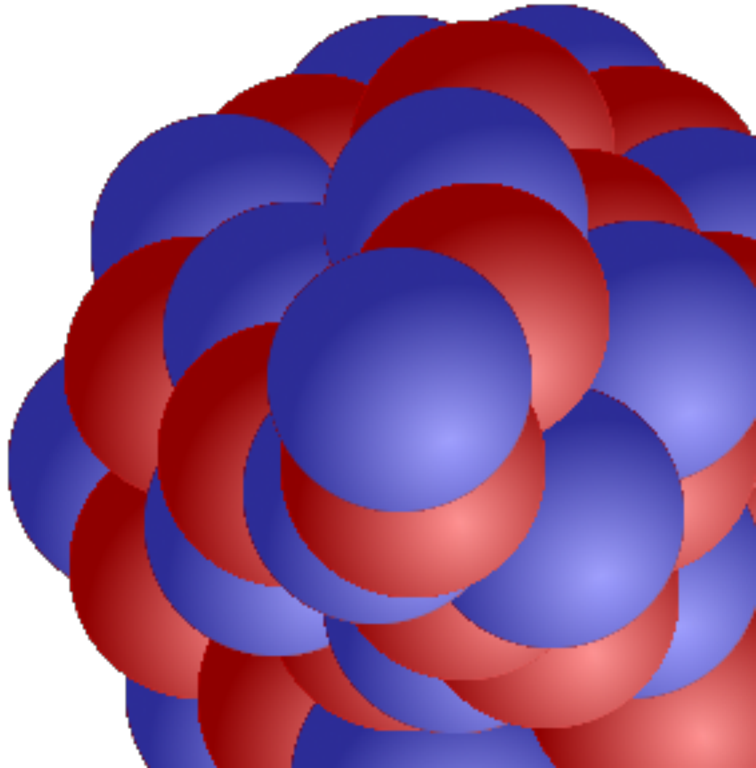
Low-energy atomic levels which cannot satisfy these rules towards the atomic ground state will trap electrons with no (easy) means of decay.

Metastable states

$$s \leftrightarrow p,\ p \leftrightarrow d,\ d \leftrightarrow f,\ \ldots$$



Atomic transitions

More math?!

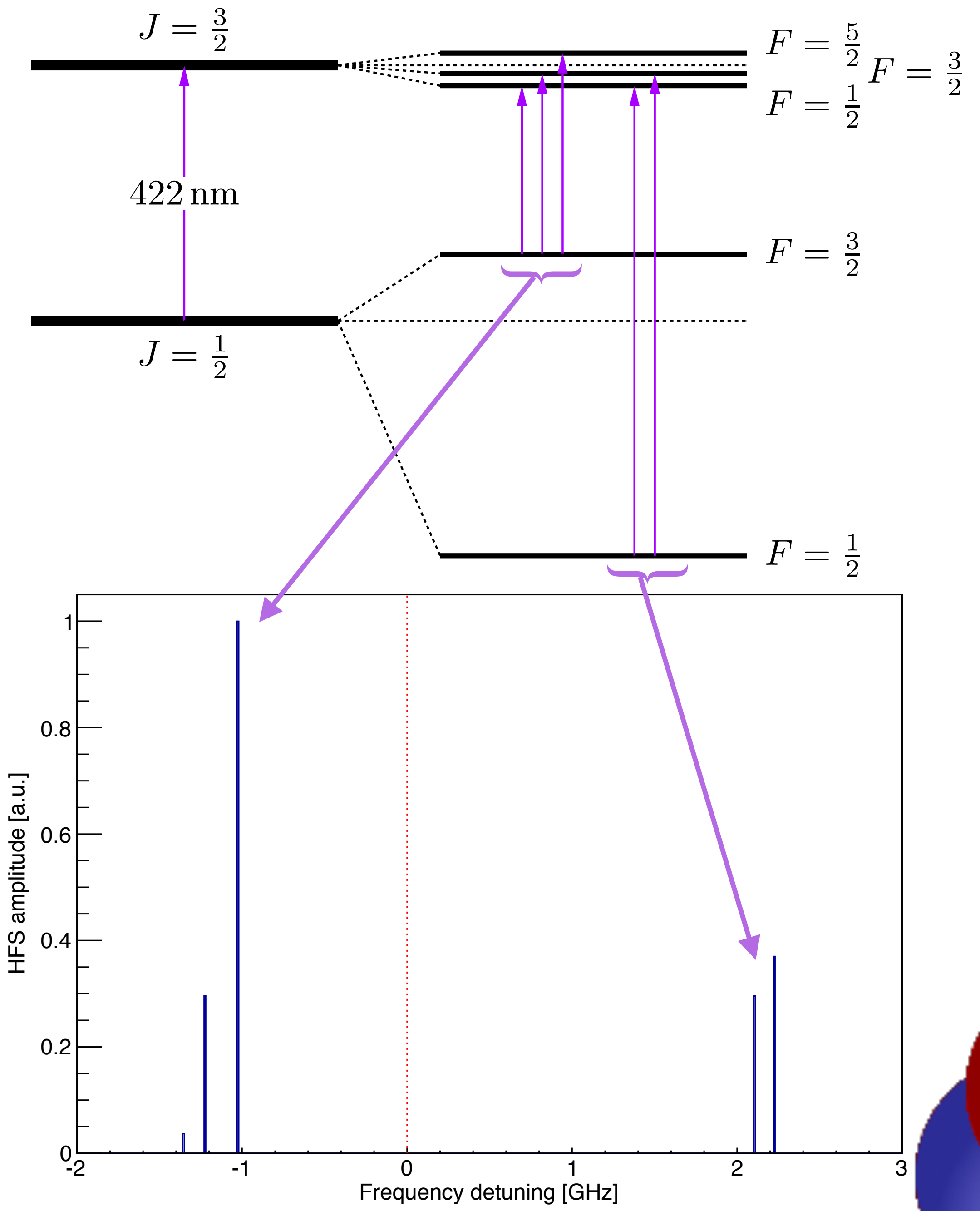
$$\langle F_f, m_f | \boldsymbol{e}\cdot\mathbf{d} | F_i, m_i \rangle$$

$$\left(2F_i+1\right)\left(2F_j+1\right)$$

X

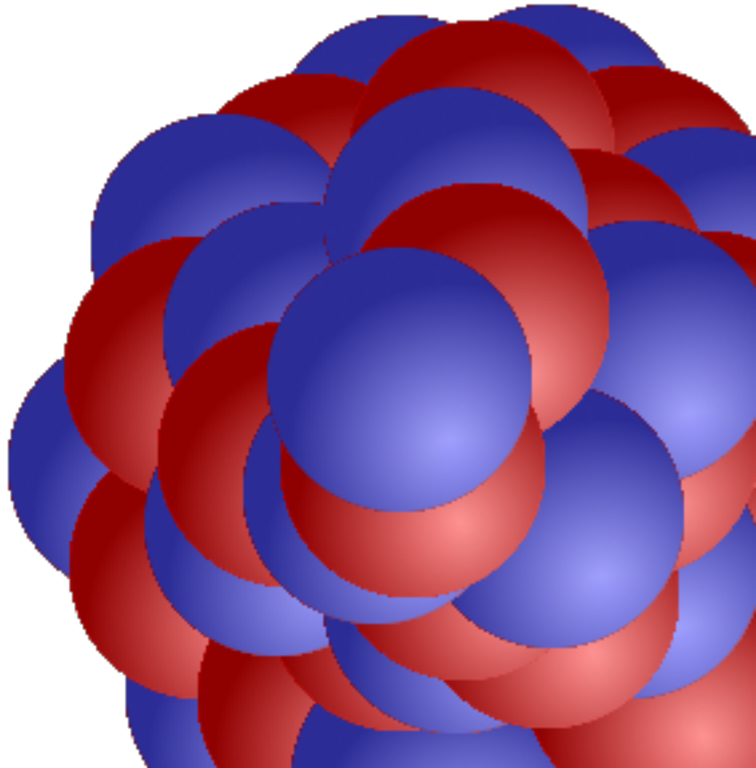
$$\begin{pmatrix} F_f & 1 & F_i \\ -m_f & 0 & m_i \end{pmatrix}^2 \begin{Bmatrix} J_f & F_f & I \\ F_i & J_i & 1 \end{Bmatrix}^2$$

Selection rules (i.e. number of transitions) and relative amplitudes are spin dependent and can be used to determine *I*



Intensities are proportional to the overlap of the final and initial quantum states under the action of the electric dipole operator

Hyperfine transitions



4 ways of measuring the nuclear spin!

Atomic transitions

More perturbations

$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

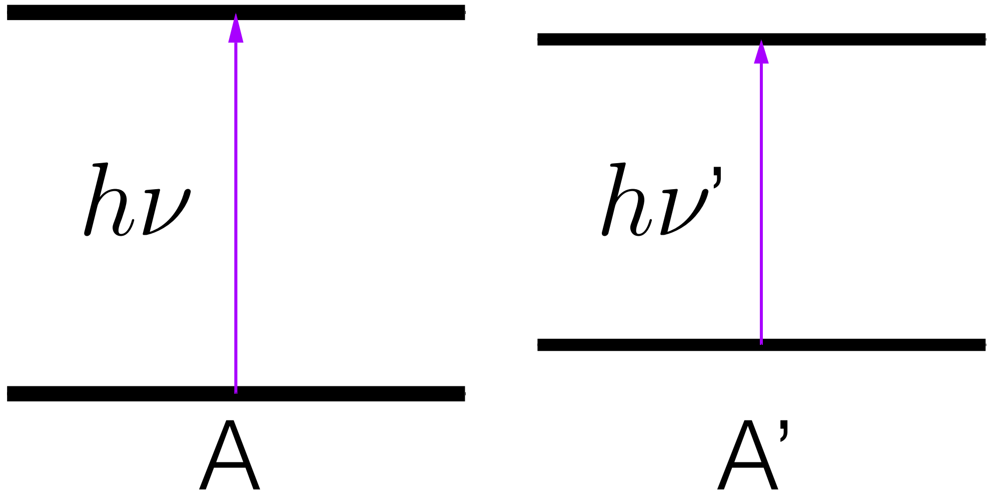
Mass shift

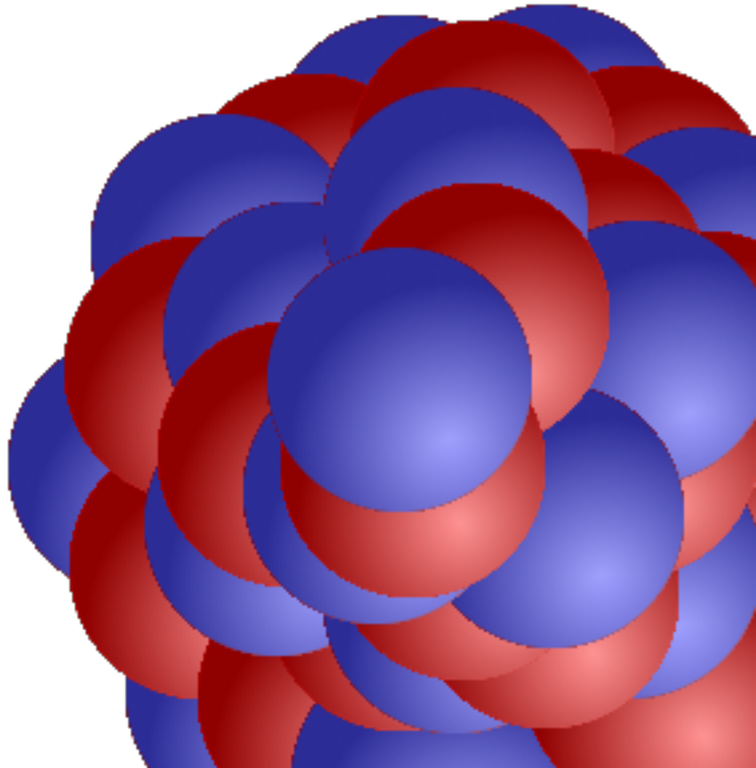
From one isotope to the next, the reduced mass of the nucleus + electron system varies, giving rise to a mass shift, scaling with A^{-2}

Field shift

From one nuclear state to the next, the charge distribution within the nucleus may vary, perturbing electron orbitals with a non-vanishing overlap with the nucleus

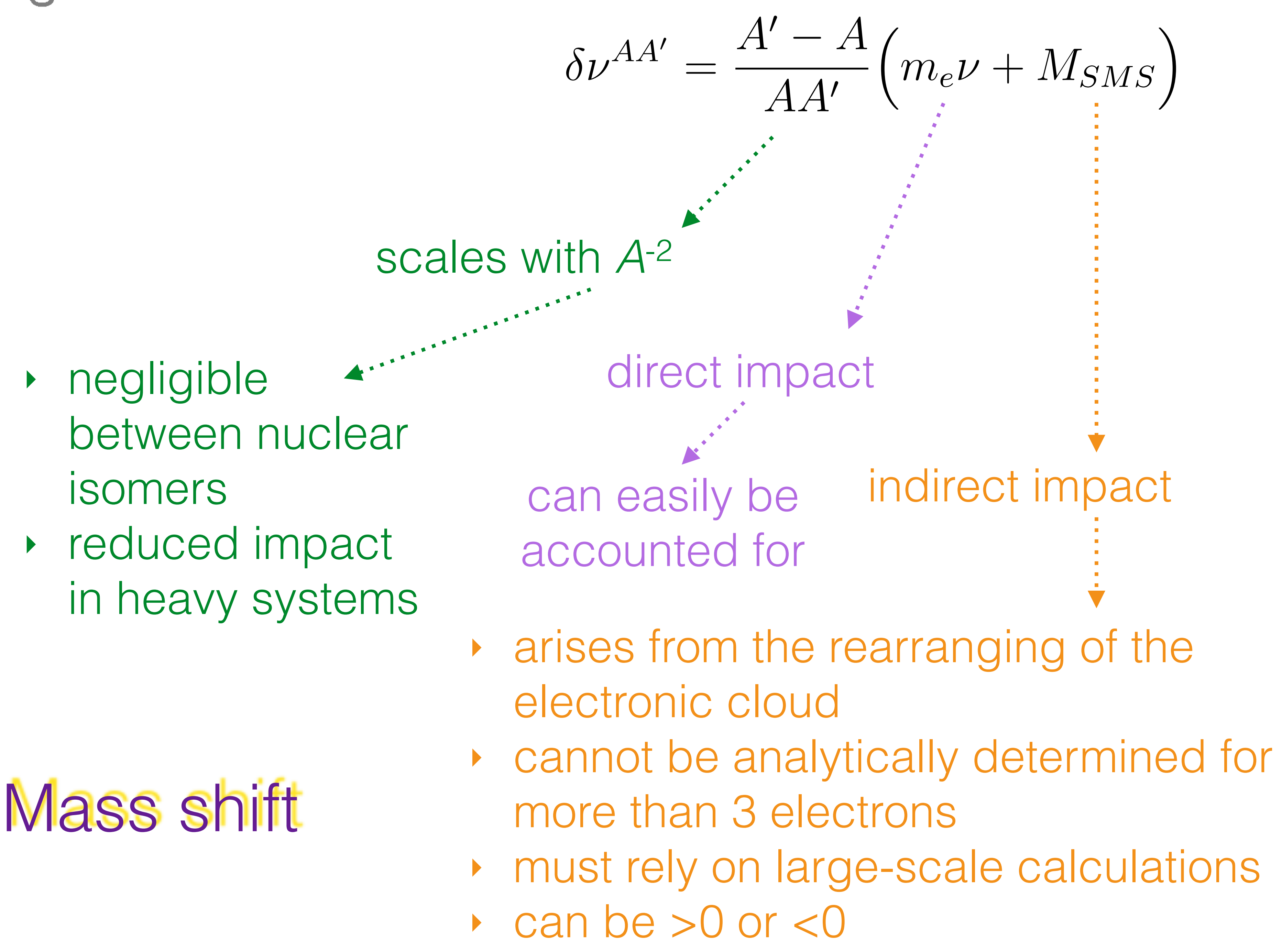
Isotope shift





Isotope shift

More details



$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right)$$

scales with A^{-2}

- negligible between nuclear isomers
- reduced impact in heavy systems

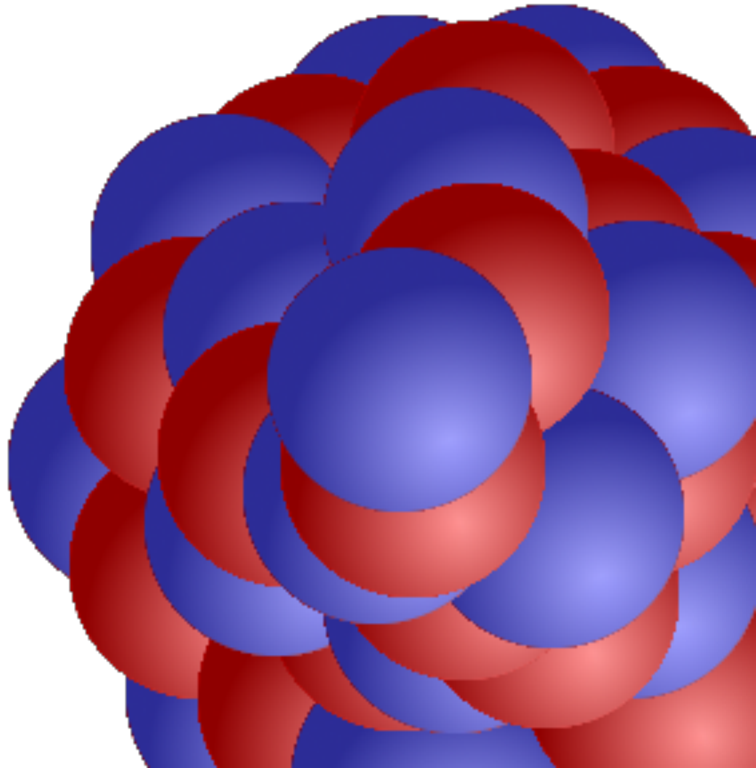
direct impact

can easily be accounted for

indirect impact

- arises from the rearranging of the electronic cloud
- cannot be analytically determined for more than 3 electrons
- must rely on large-scale calculations
- can be >0 or <0

Mass shift



Isotope shift

More details

$$\delta\nu = F\delta\langle r^2\rangle$$

M_{SMS} & F are transition specific !

scales with Z

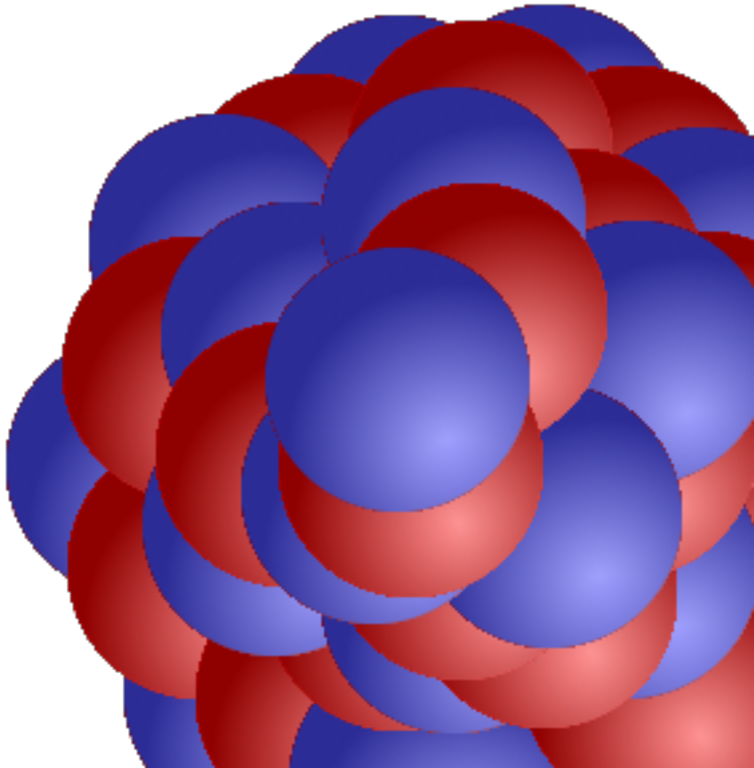
- sole contribution between nuclear isomers
- increased impact in heavy systems

higher moments, e.g. $\delta\langle r^4\rangle$ can be accounted for directly

no analytical solution

- must rely on large-scale calculations for more than 3 electrons
- can be >0 or <0

Field shift
a.k.a. Volume shift



Isotope shift

$$\mu_{AA'} = \frac{AA'}{A'-A}$$

Experimental approach to avoid calculations

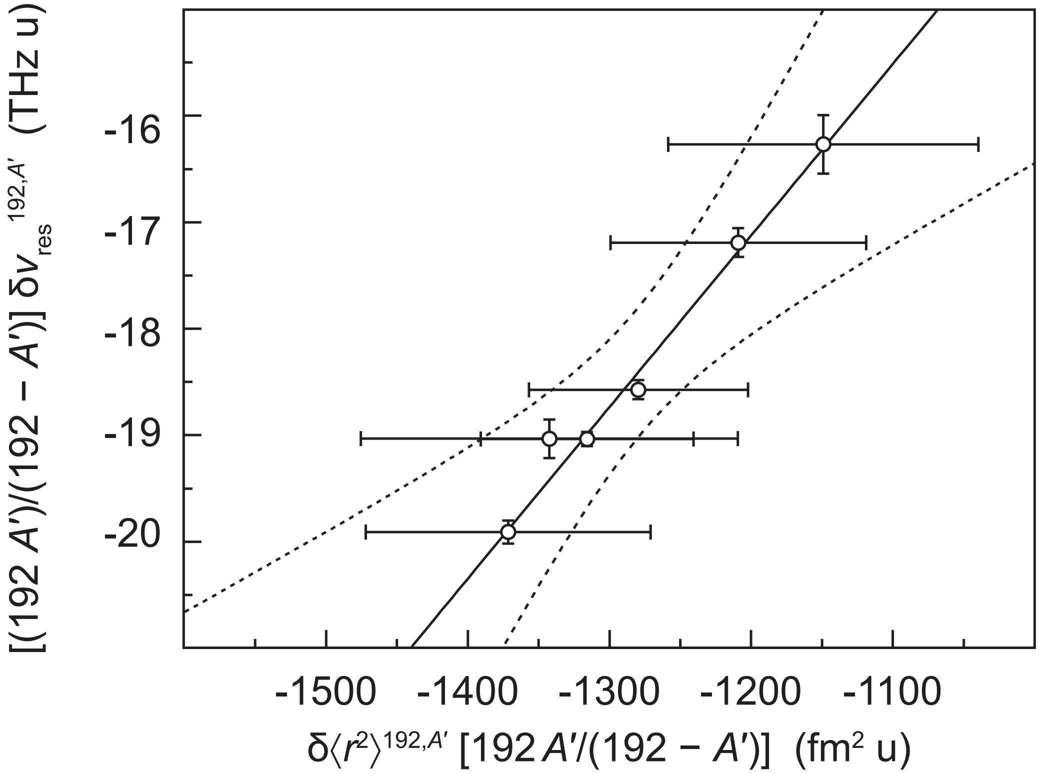
$$\mu_{AA'}\delta\nu^{AA'} = M + F\mu_{AA'}\delta\langle r^2\rangle^{AA'}$$

Experimental input from laser / optical spectroscopy

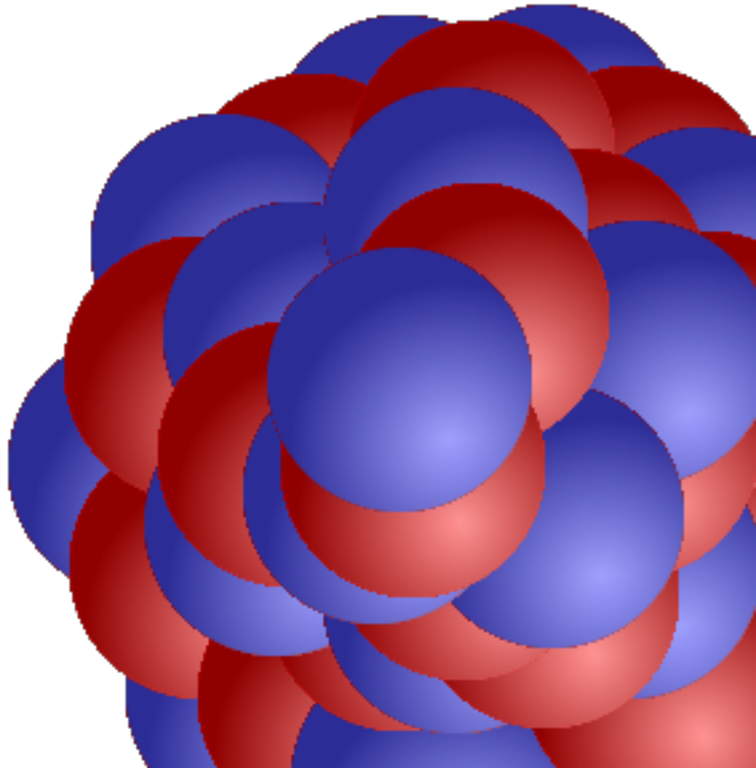
y intercept

slope

Experimental input from electron scattering, muonic decay, *K* x-ray spectroscopy



King plot



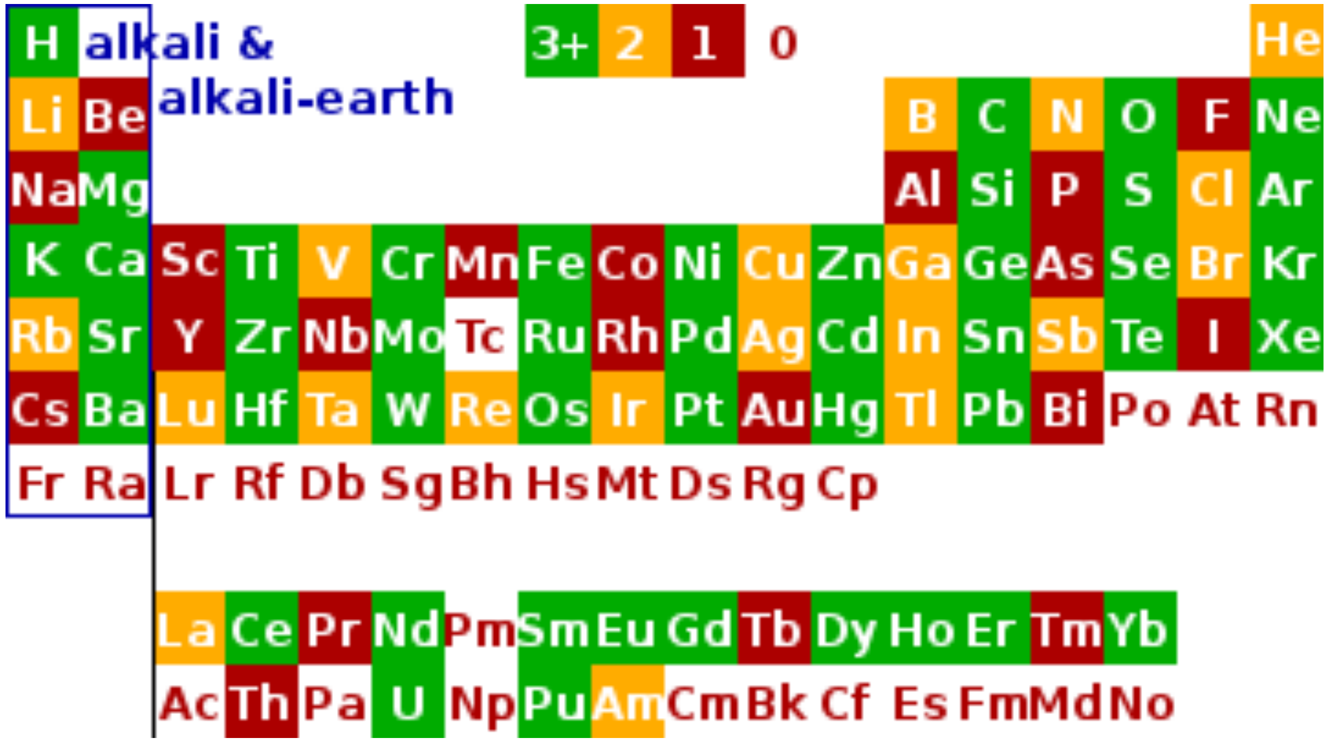
Isotope shift

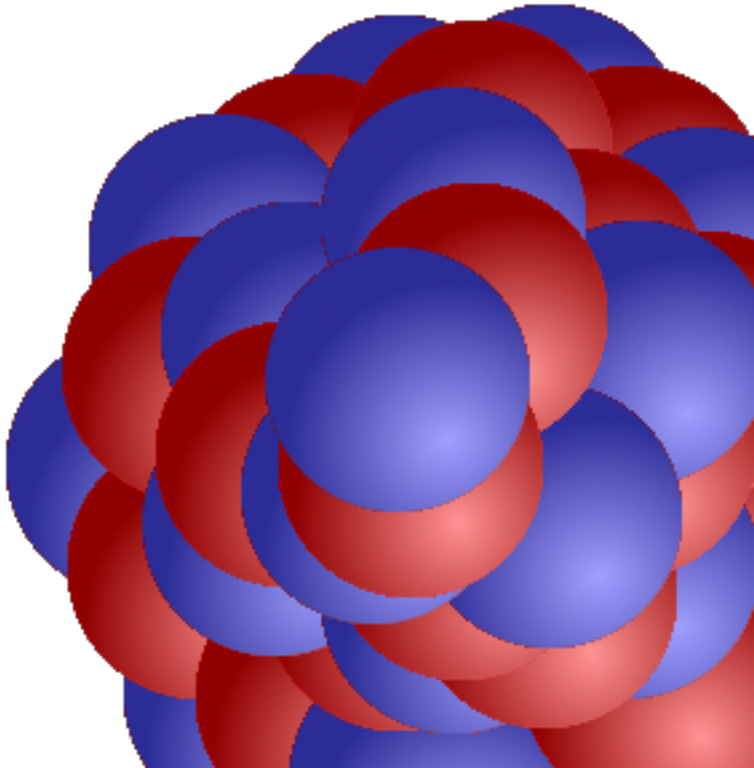
$$\mu_{AA'} = \frac{AA'}{A'-A}$$

The art of fitting a straight line

$$\mu_{AA'}\delta\nu^{AA'} = M + F\mu_{AA'}\delta\langle r^2\rangle^{AA'}$$

2 points => fitting a straight line
1 point => reference isotope
TOTAL => 3 data points minimum





King plot

Isotope shift

$$\mu_{AA'} = \frac{AA'}{A'-A}$$

Relating and testing

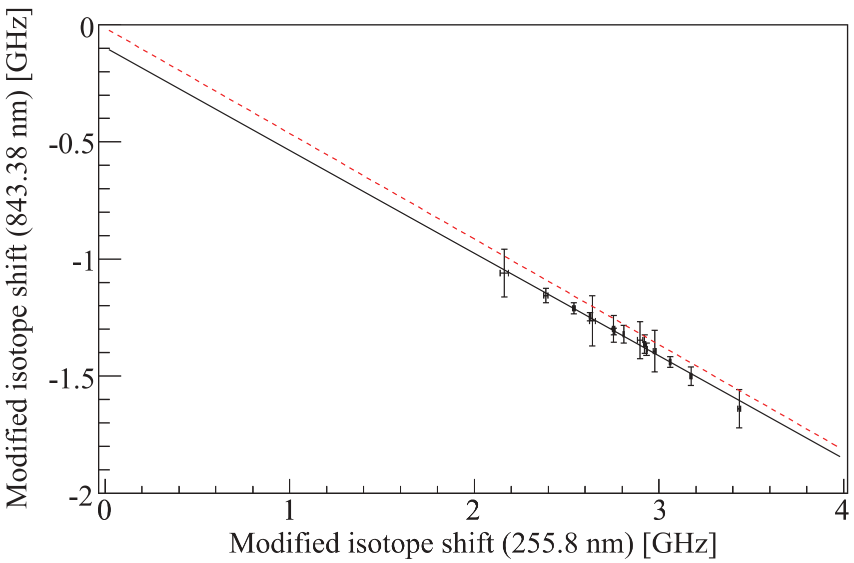
$$\mu_{AA'}\delta\nu_2^{AA'} = \frac{F_2}{F_1}\mu_{AA'}\delta\nu_1^{AA'} + \left(M_2 - \frac{F_2}{F_1}M_1\right)$$

Transition 2

slope

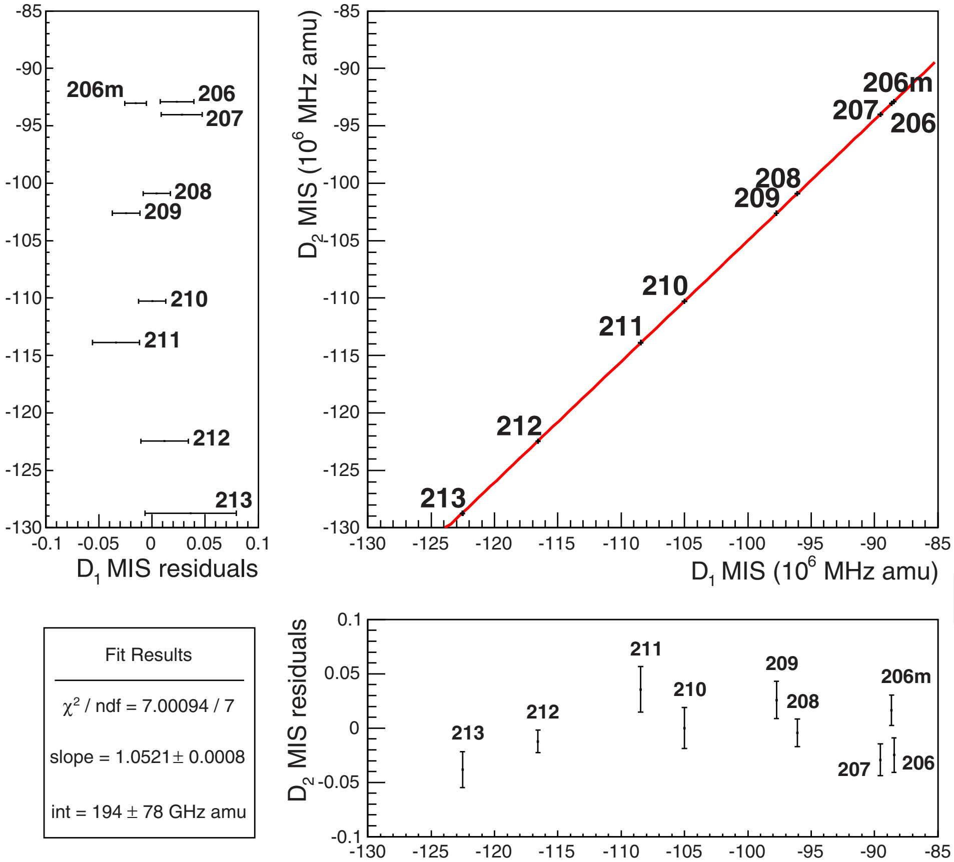
Transition 1

y intercept relates the mass shifts to one another



Modified King plot

Many more data available

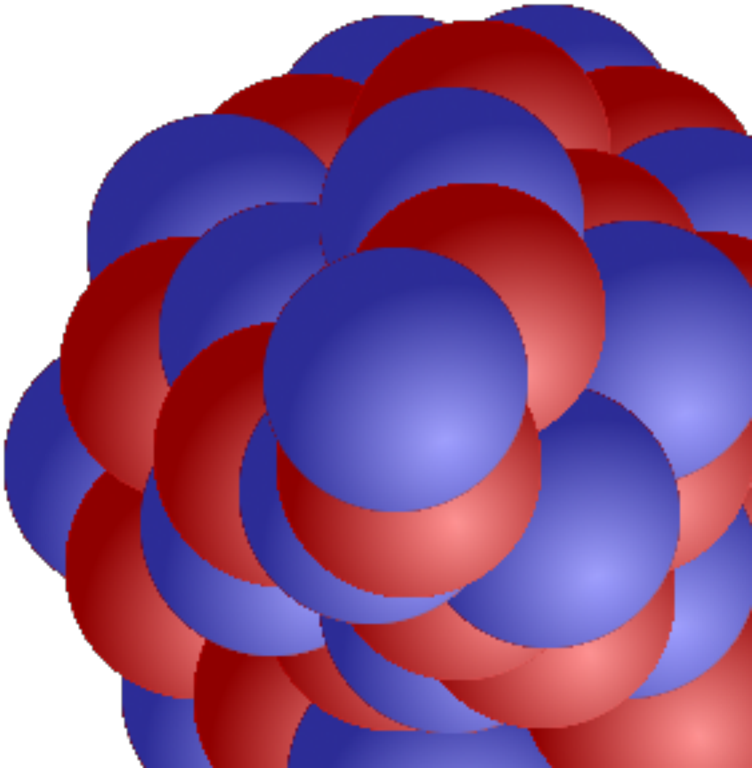


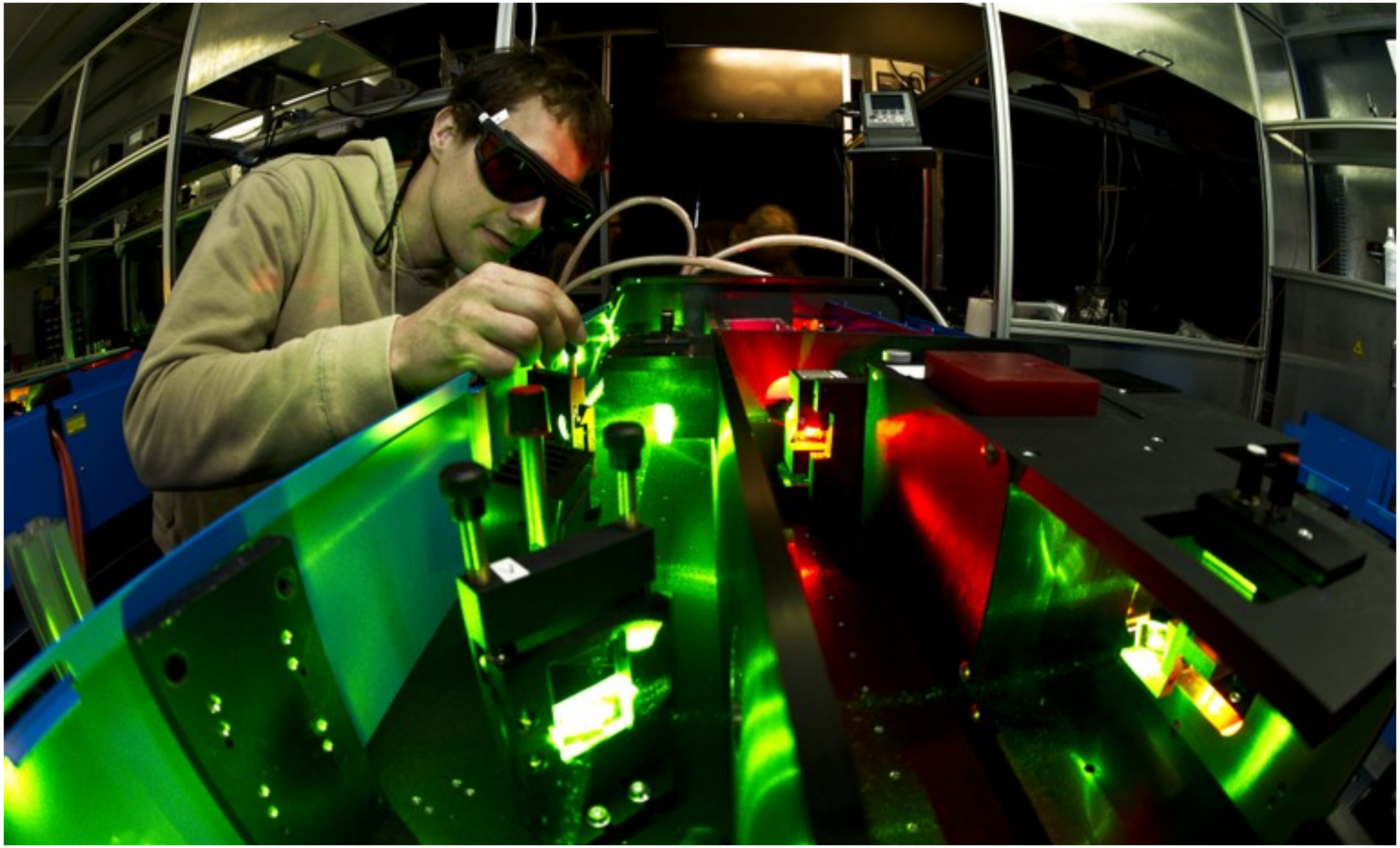
Fit Results

χ^2 / ndf = 7.00094 / 7

slope = 1.0521 ± 0.0008

int = 194 ± 78 GHz amu

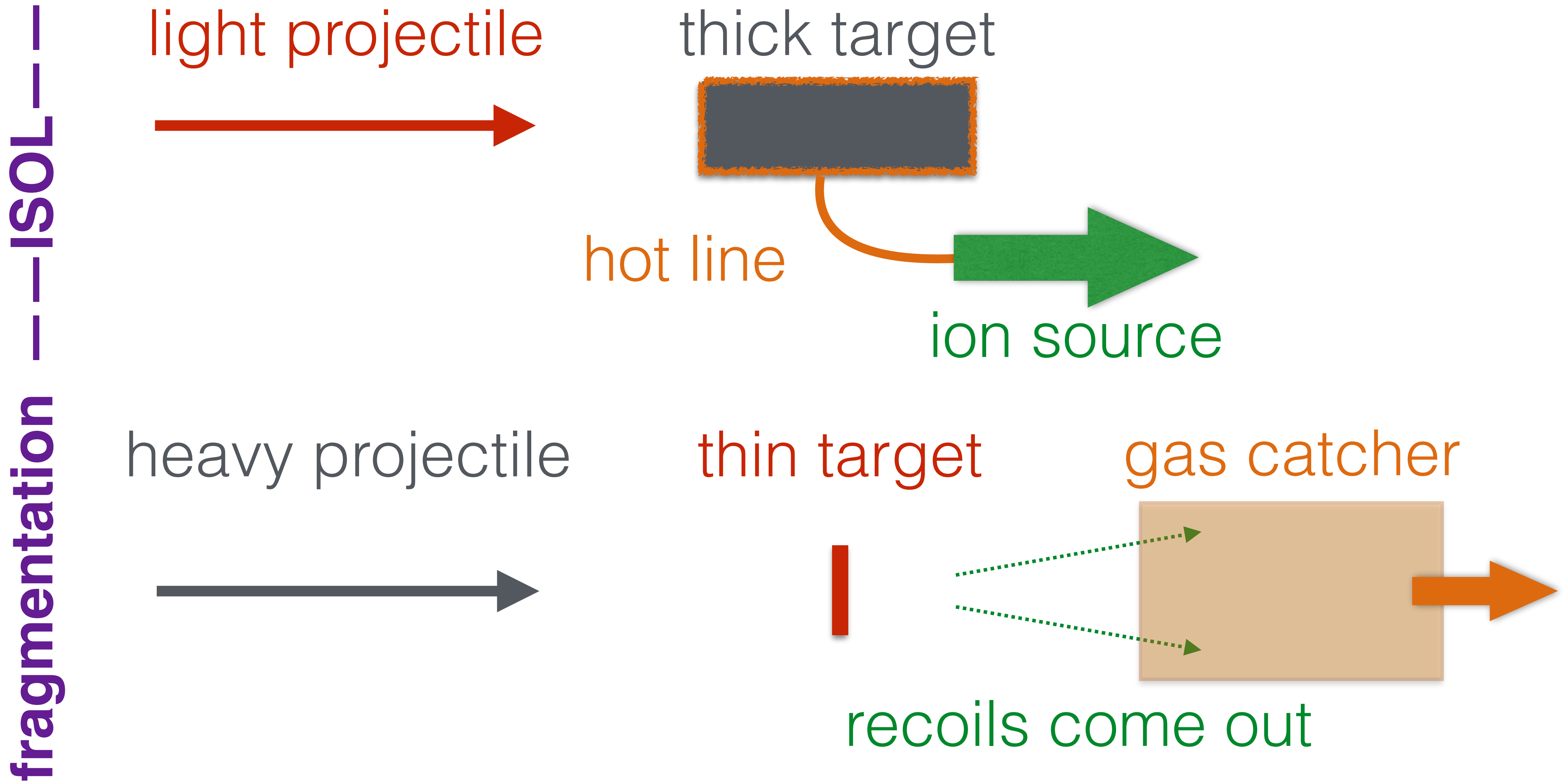




RIB Production

Isotope production

Start with your favourite facility



Beam properties

ISOL

- Thick target
  - no refractory elements
  - slow (>ms) extraction
- Mass separation
  - high purity
- Bespoke ion sources
  - surface source for low IP
  - plasma for gases
    - ➡ non discriminate

fragmentation

- Thin target
  - all elements
  - fast extraction
- Pre mass separation
  - low purity
- Gas catcher
  - slow thermalisation (>ms)
  - survival
    - ➡ non discriminate

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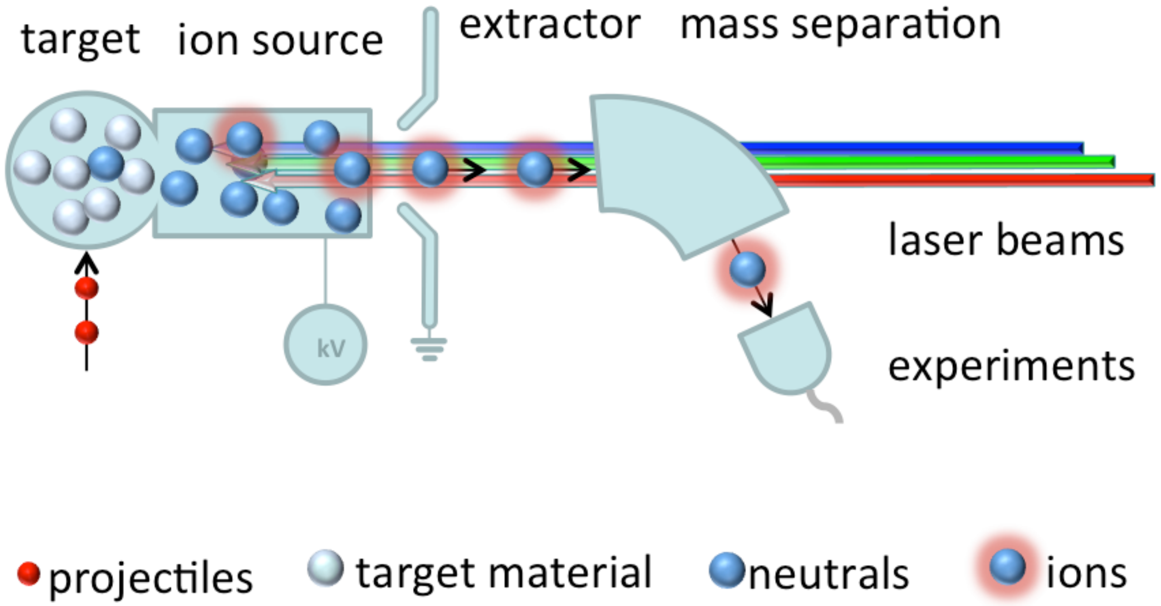
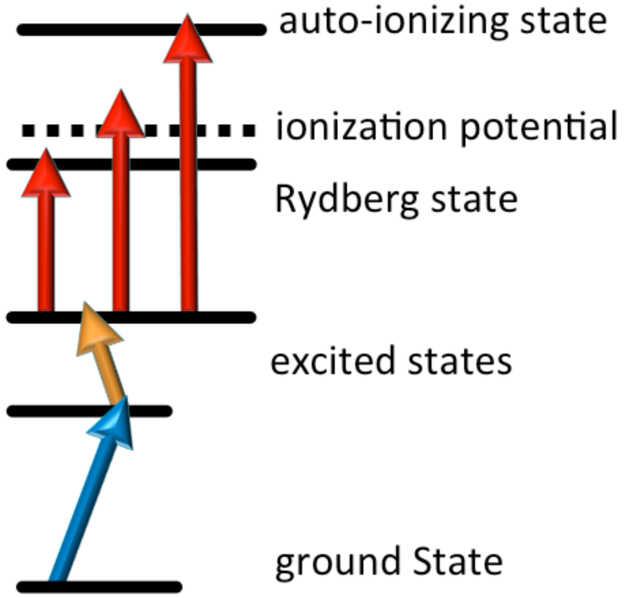
RILIS

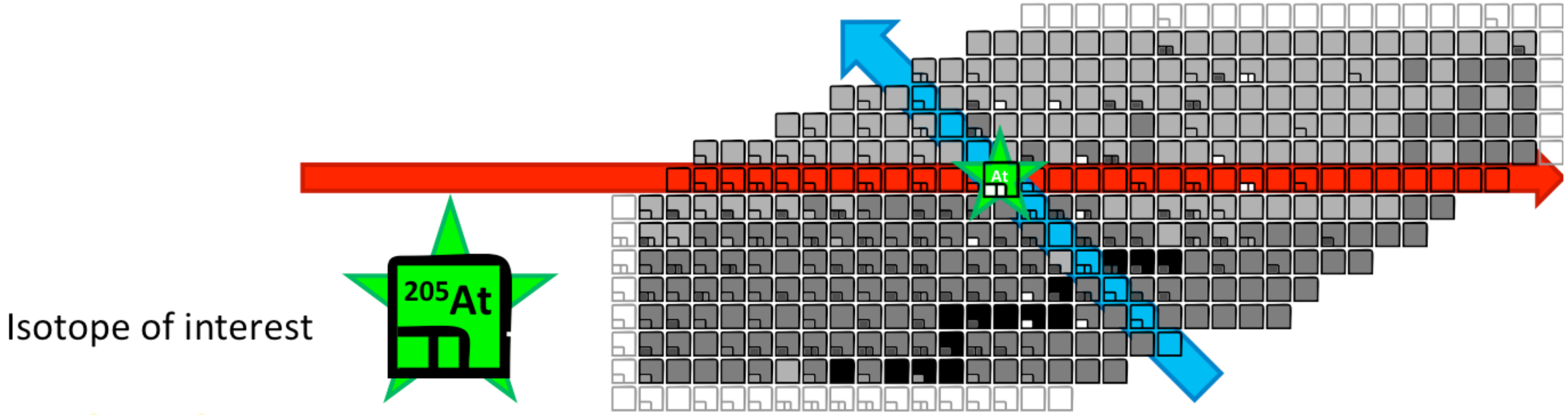
Resonance Ionisation Laser Ion Source

- Resonant transitions specific to a single element are chosen





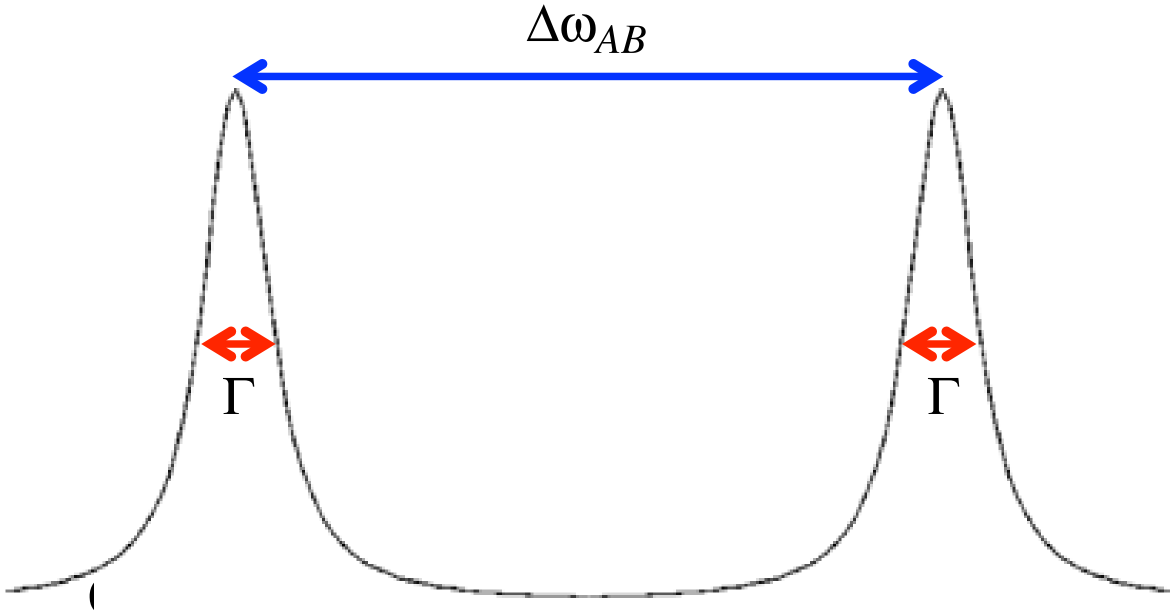
- No single transition has enough energy to non-resonantly ionise an atom directly



Everybody's favourite ion source

Selectivity

The power of a pure beam

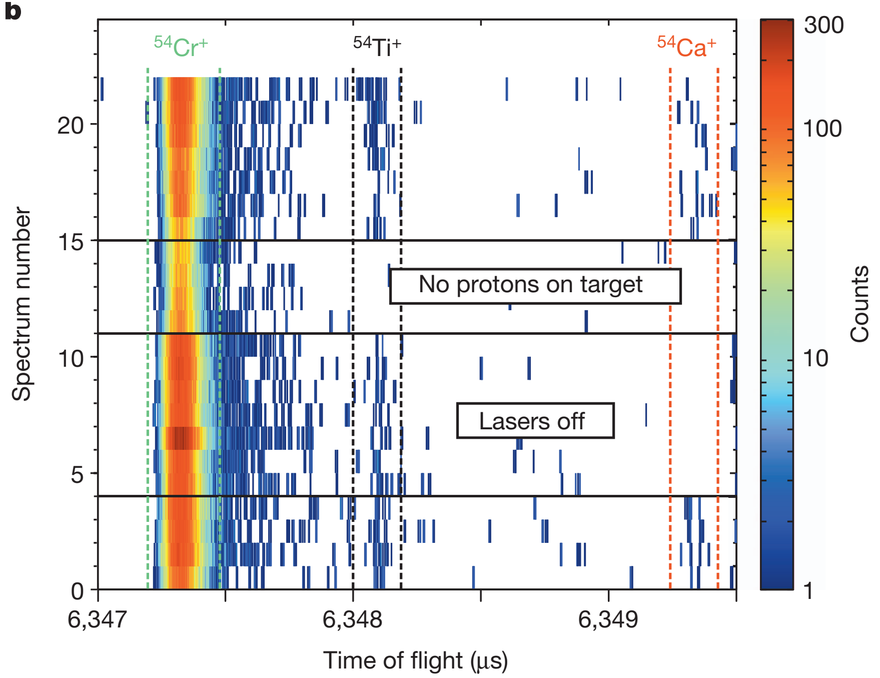


$$S = \left(\frac{\Delta\omega_{AB}}{\Gamma}\right)^2$$

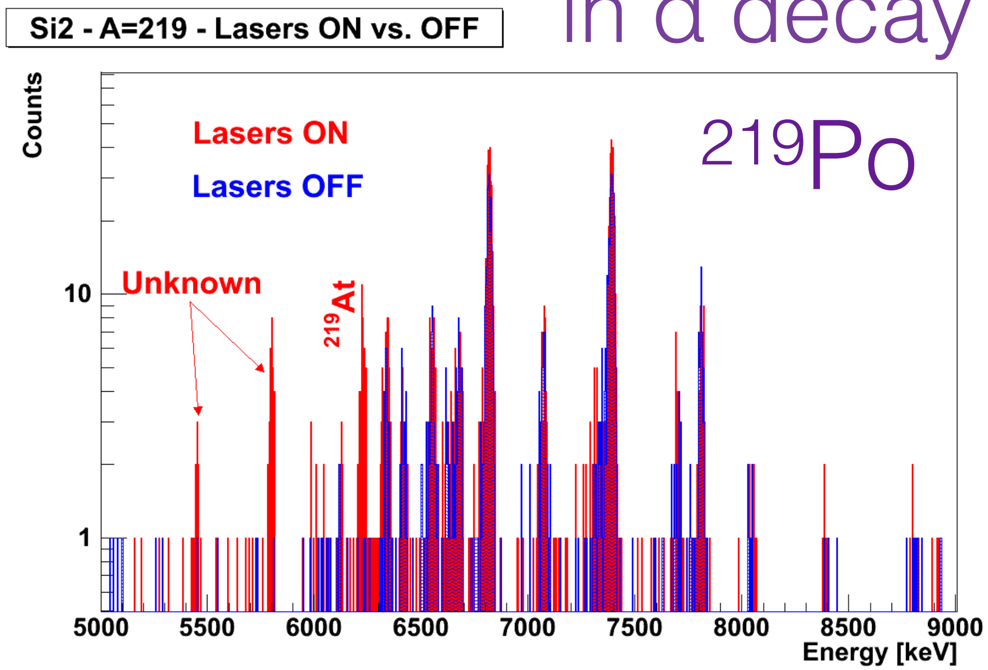
- Each resonant transition has an associated selectivity.
- The selectivity of different transitions multiplies over.

Laser ON/OFF

in mass measurement

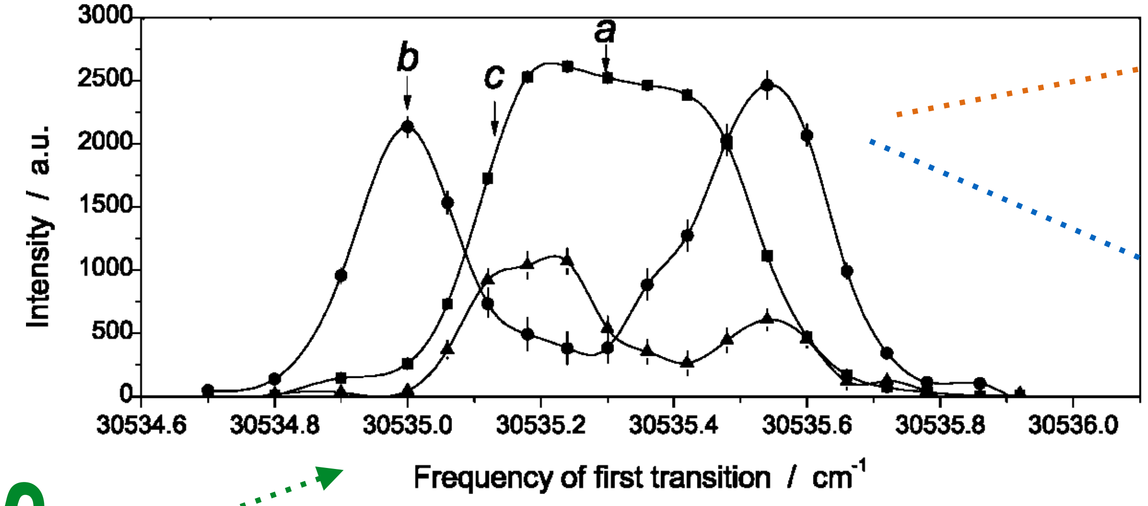


in a decay



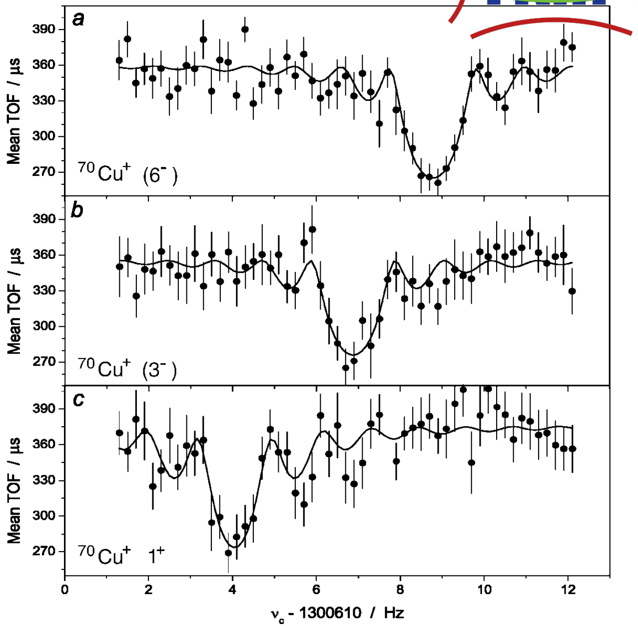
Isomeric beams

Different I means different HFS
=> enhanced selectivity

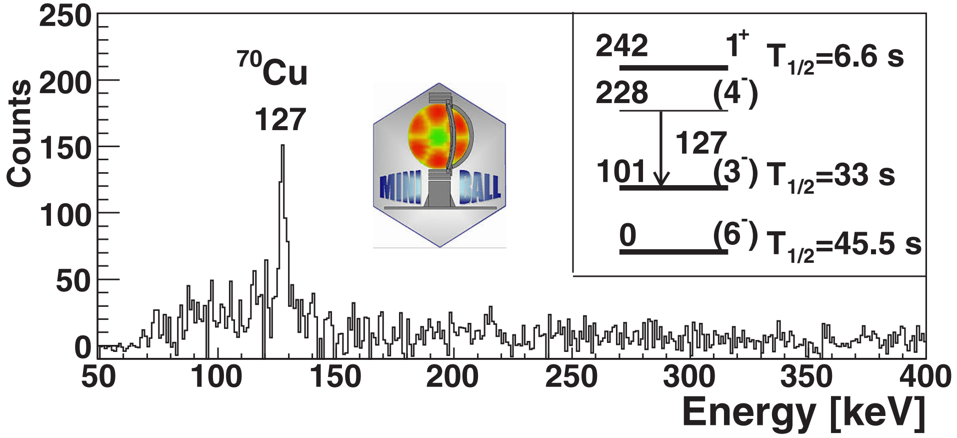


RILIS

^{70}Cu

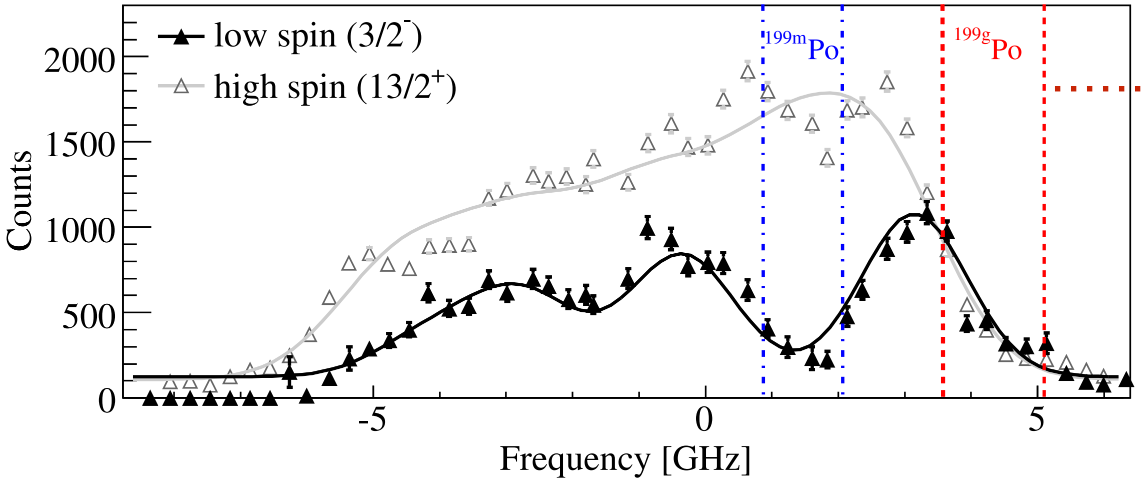


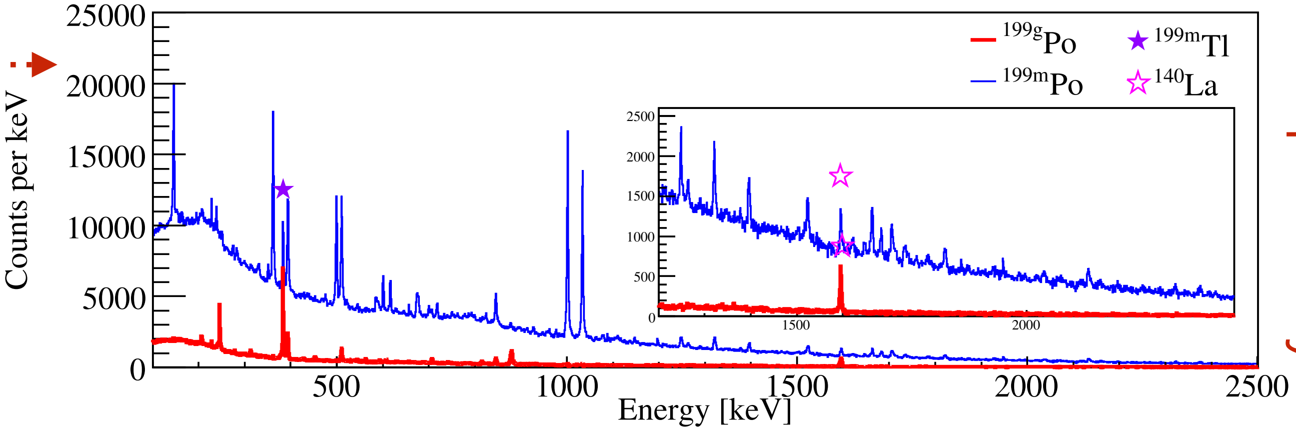
in mass measurement



in Coulomb excitation

^{199}Po





in β decay

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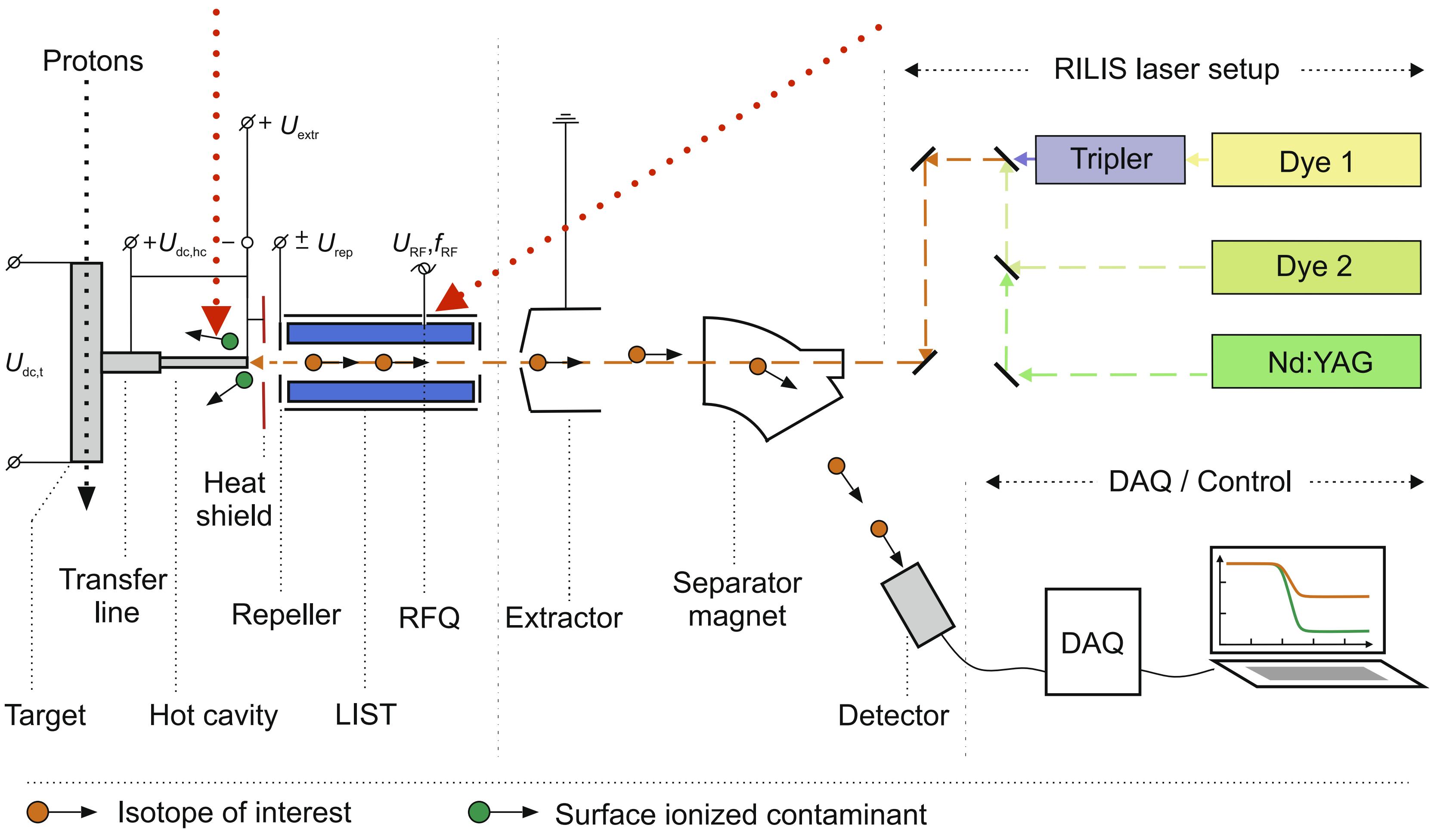
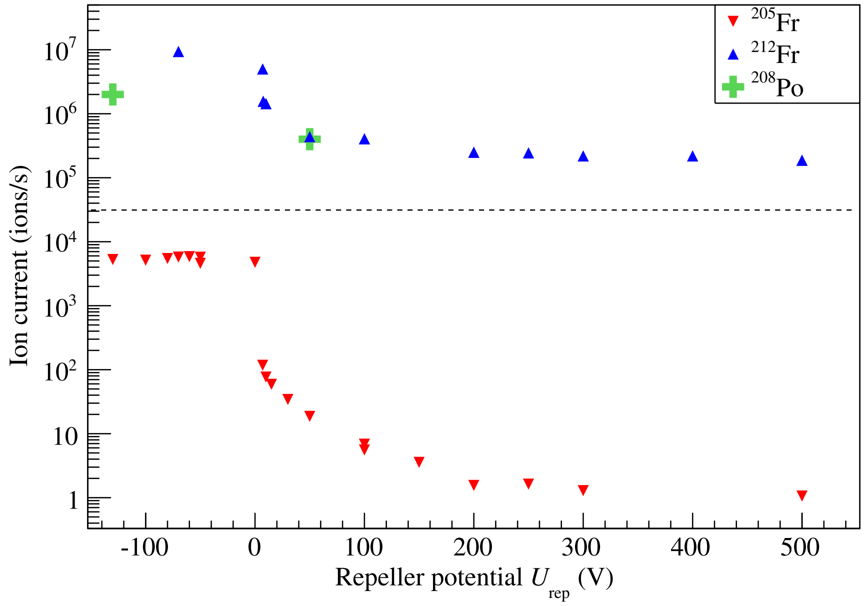
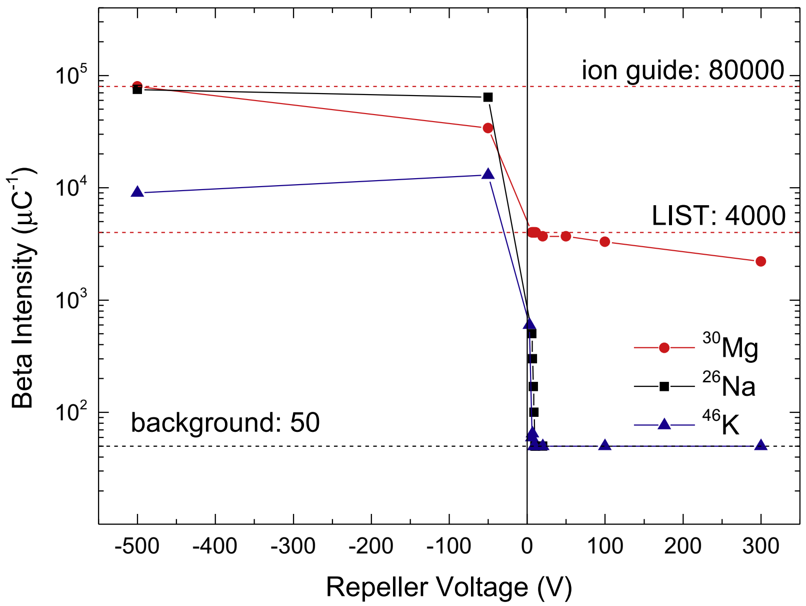
LIST

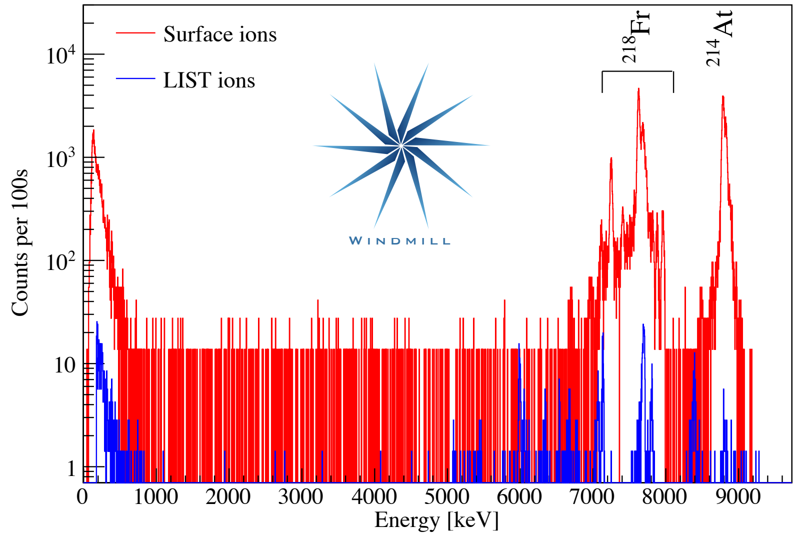
Overcoming contaminants by geometrically decoupling the **atomiser** from the **ionising volume**





repeller scans



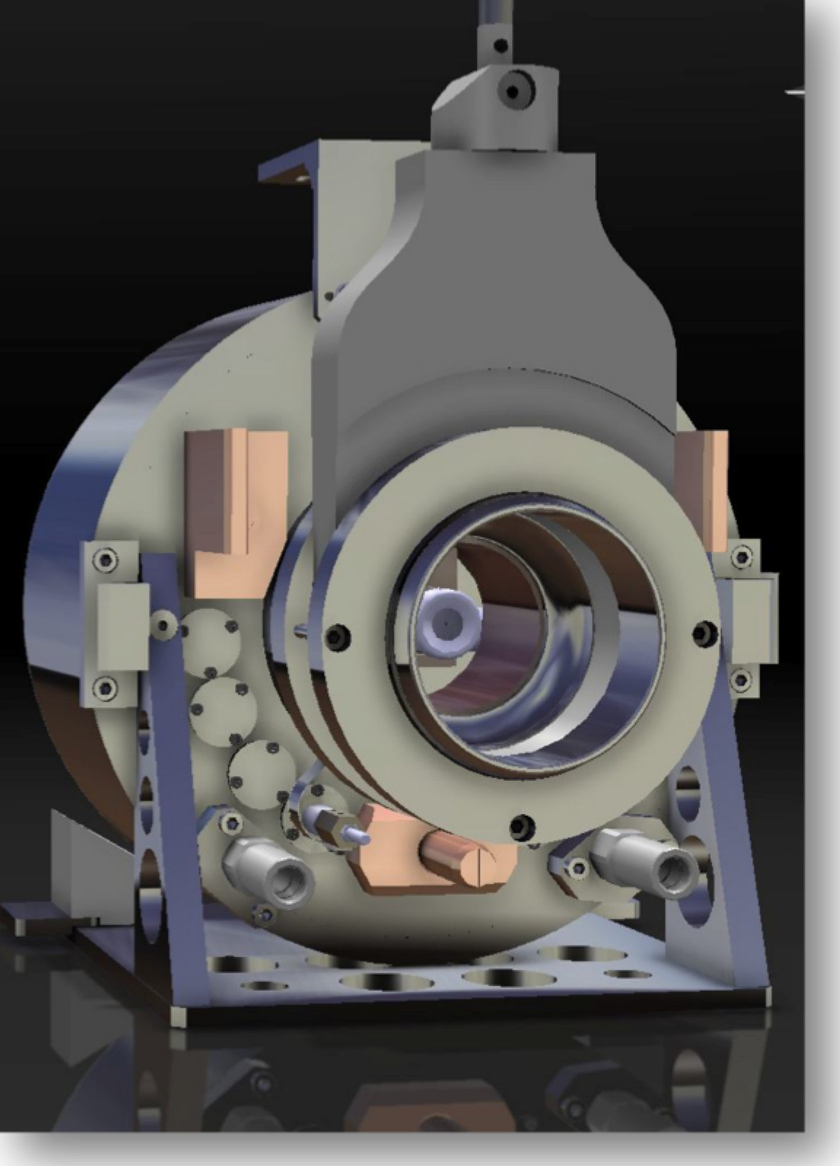


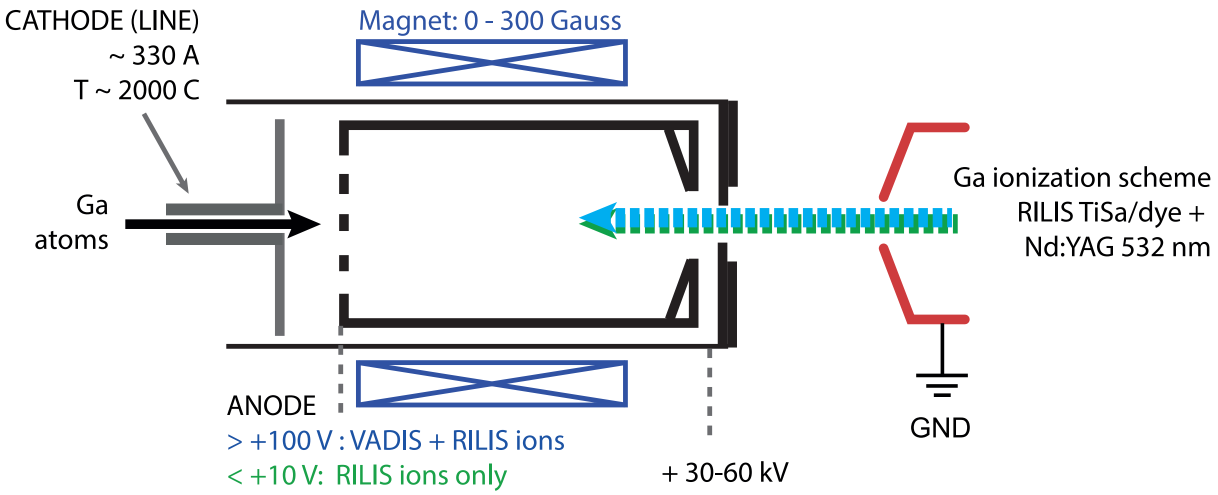
in α decay

Laser Ion Source & Trap

RILIS

VADLIS





CATHODE (LINE)
~ 330 A
T ~ 2000 C

Magnet: 0 - 300 Gauss

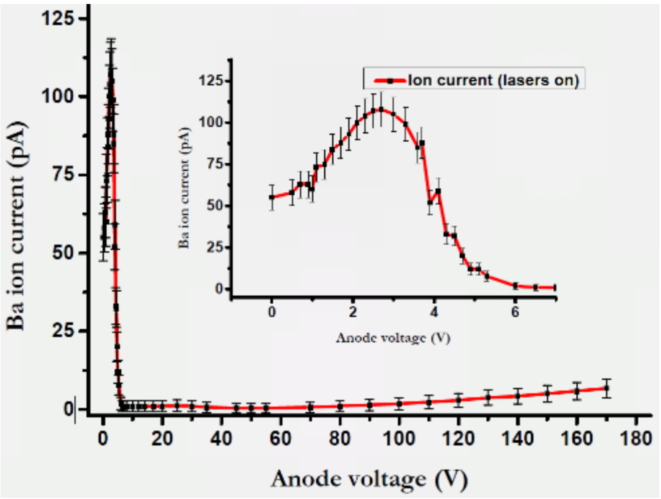
Ga
atoms

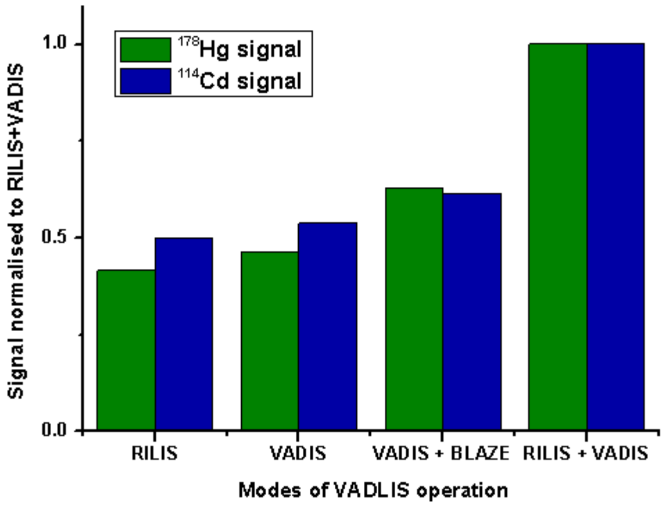
Ga ionization scheme
RILIS TiSa/dye +
Nd:YAG 532 nm

ANODE
> +100 V : VADIS + RILIS ions
< +10 V: RILIS ions only

+ 30-60 kV

GND



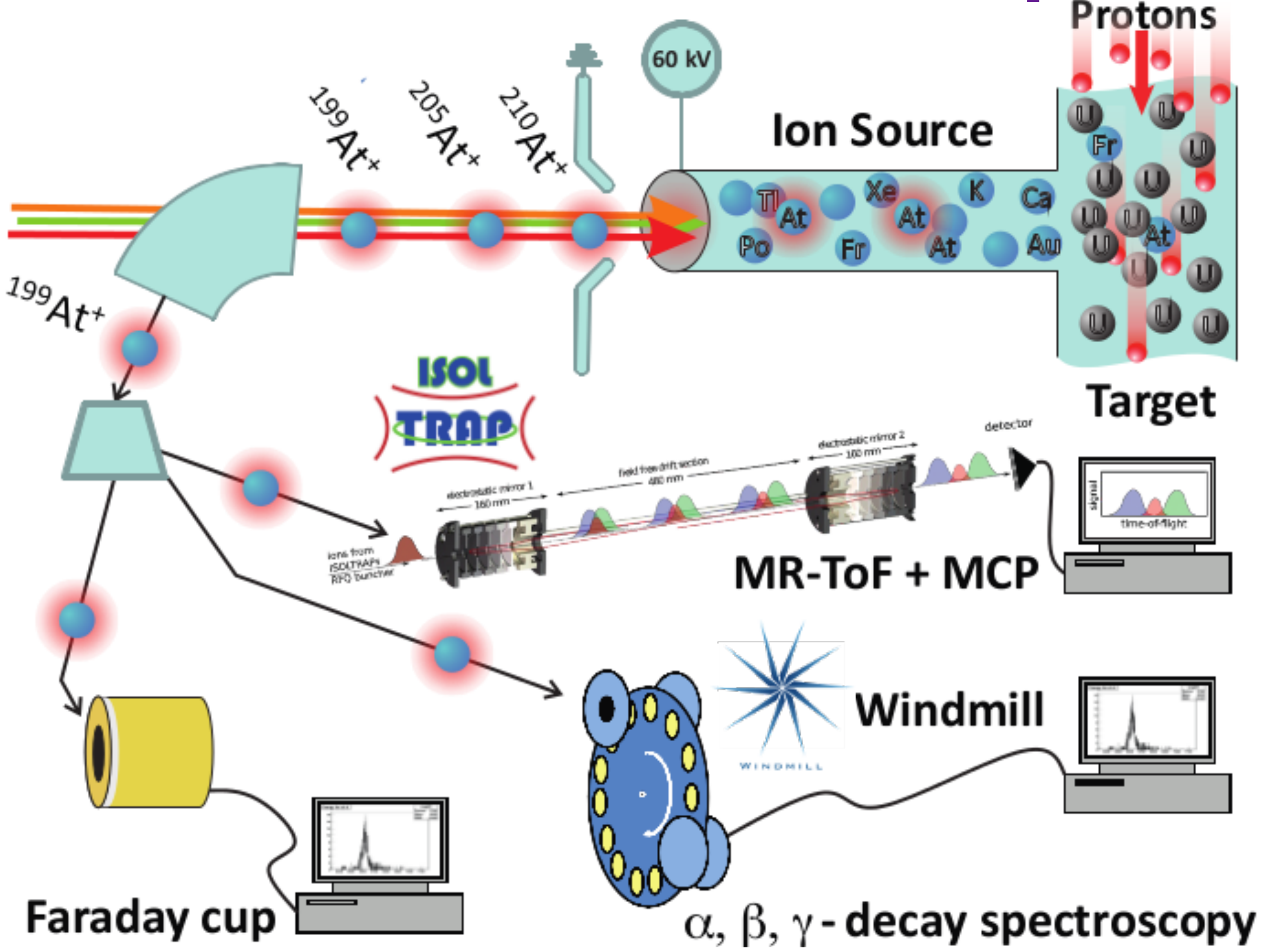


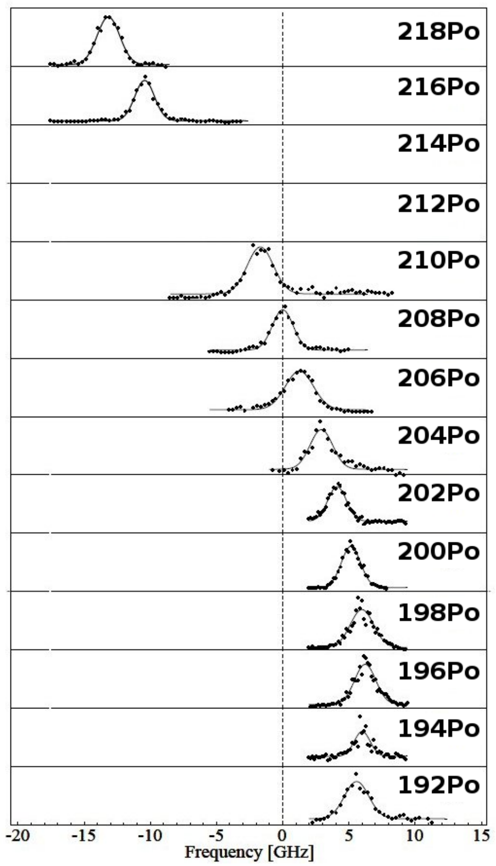
Versatility in the use of the VADIS with laser

- pure plasma
- pure laser
- mixed plasma / laser

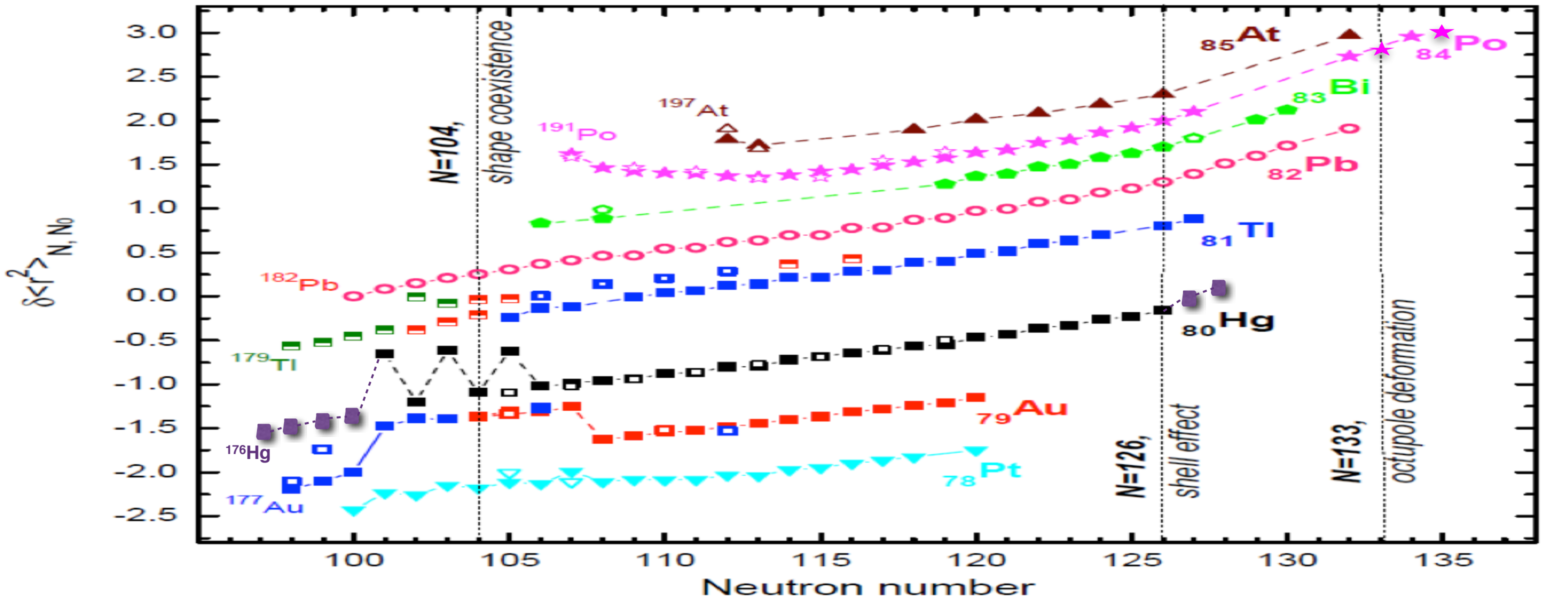
Everybody’s favourite ion source

In-source spectroscopy

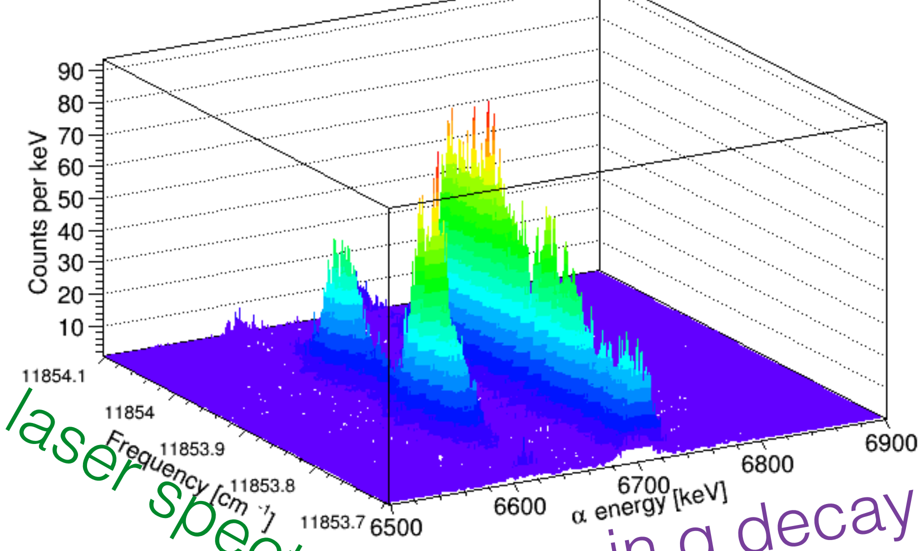




in laser spectroscopy



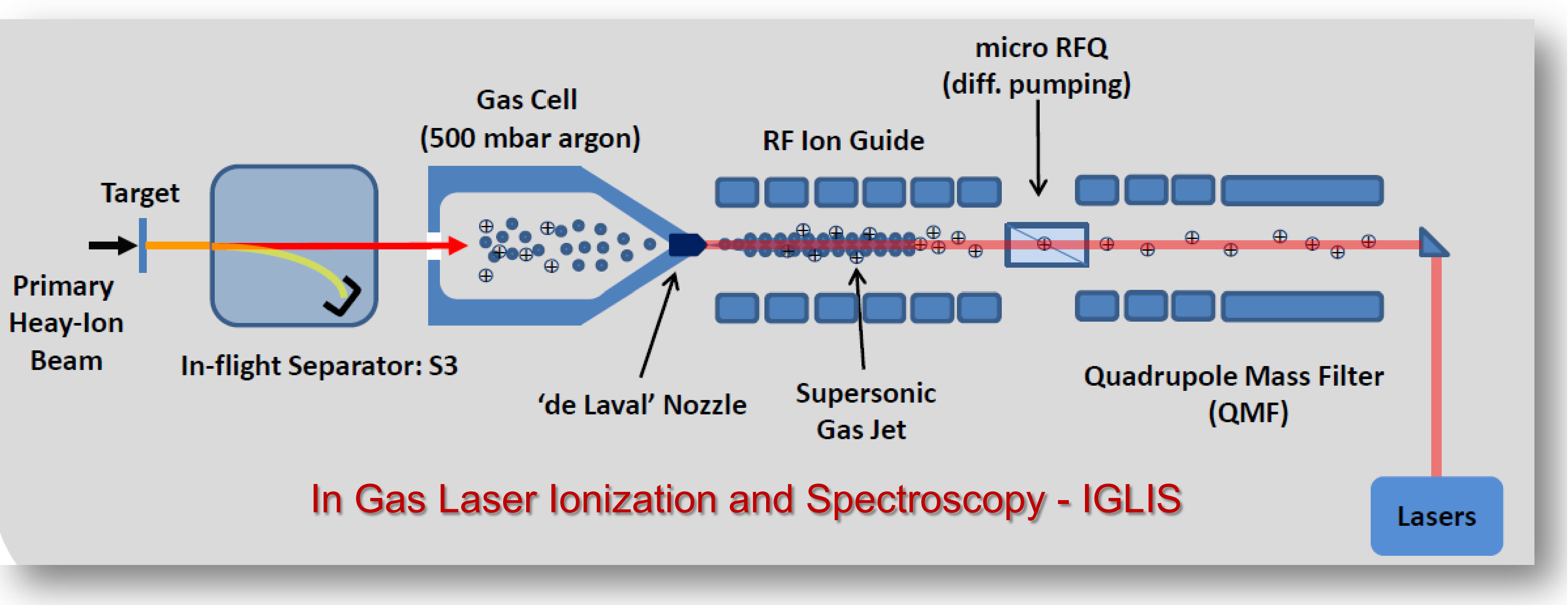
^{195}Po



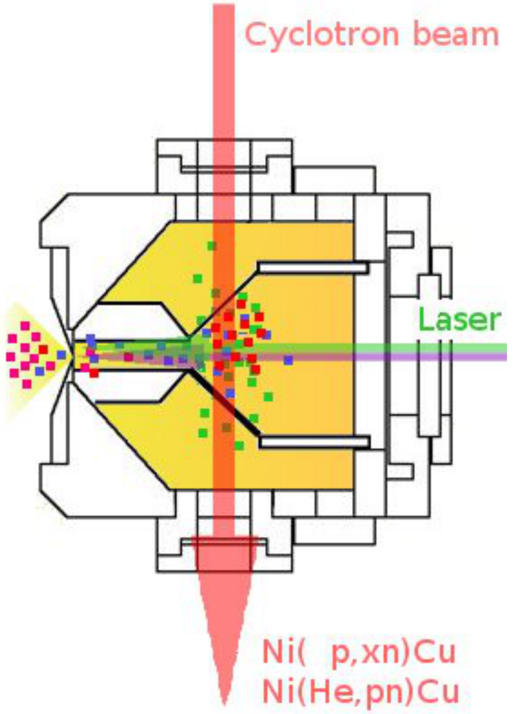
in laser spectrosc

in α decay

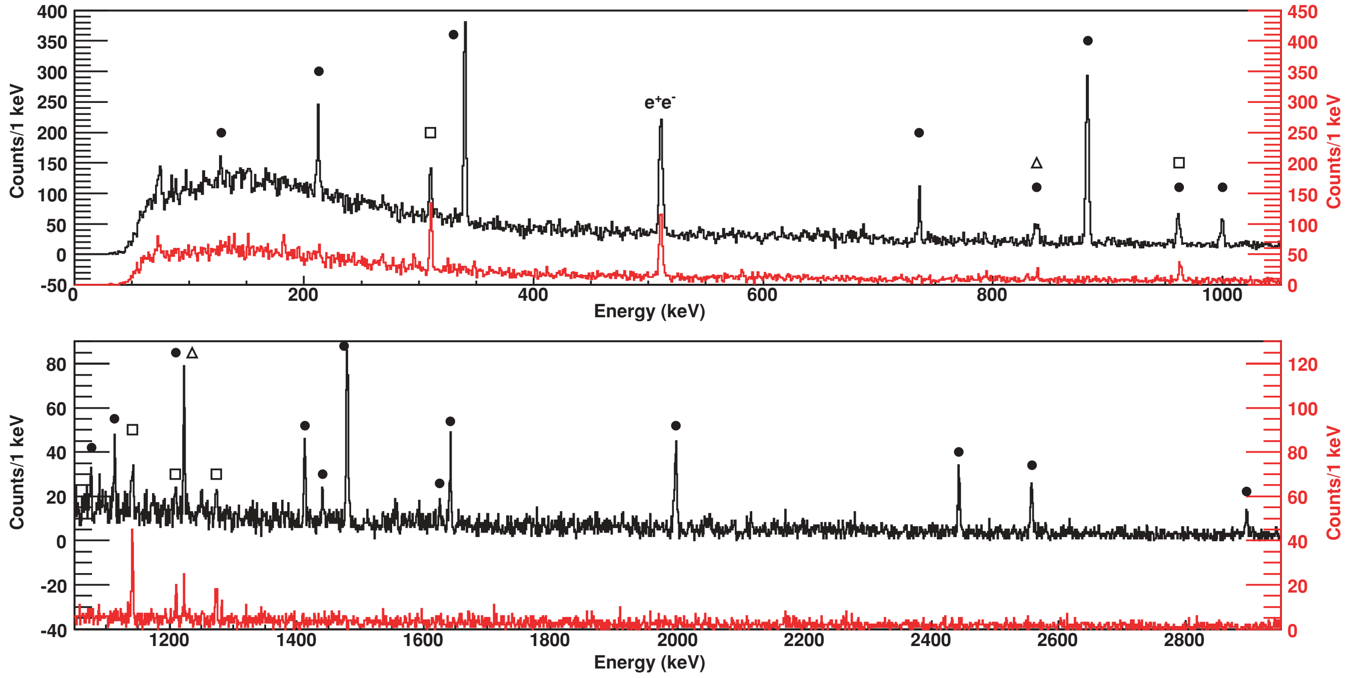
IGLIS



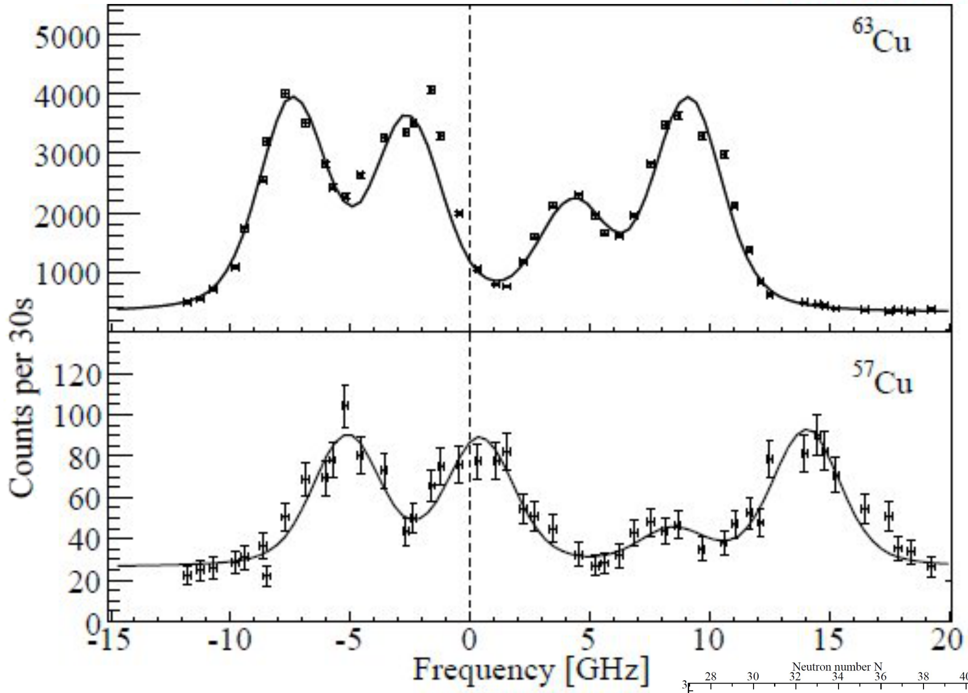
In Gas Laser Ionization and Spectroscopy - IGLIS

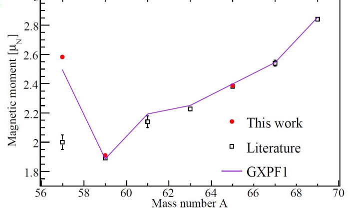


Fe vs **Co**



in β decay

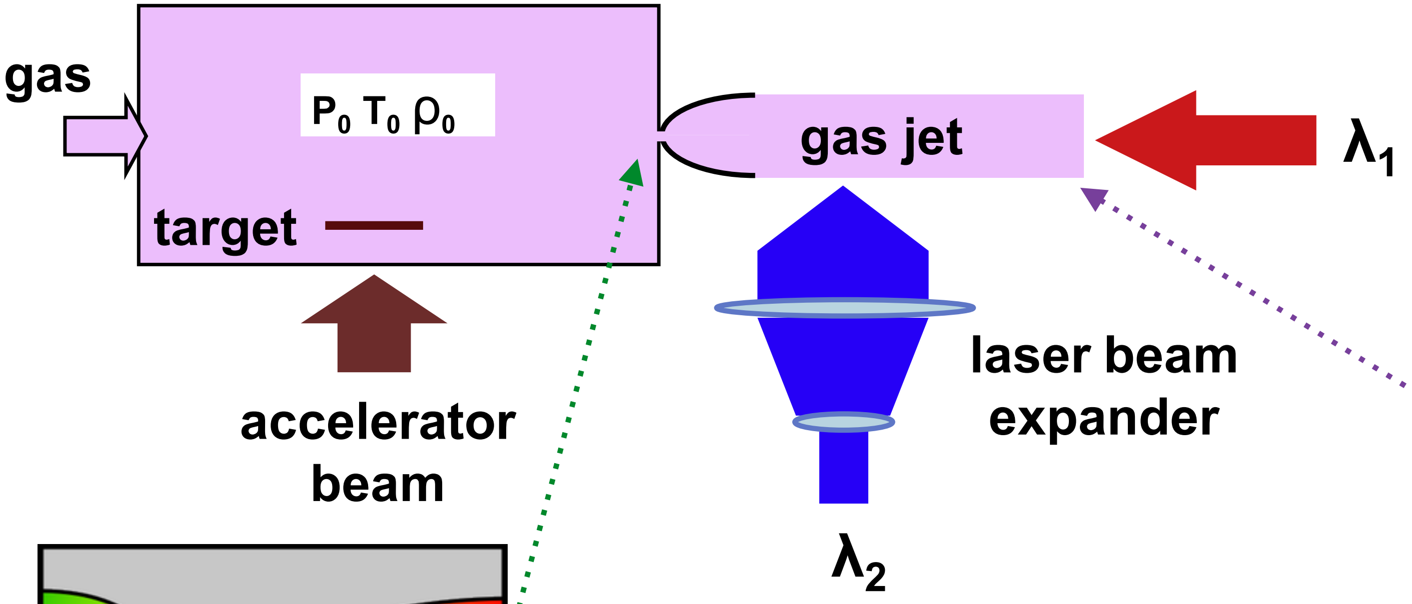


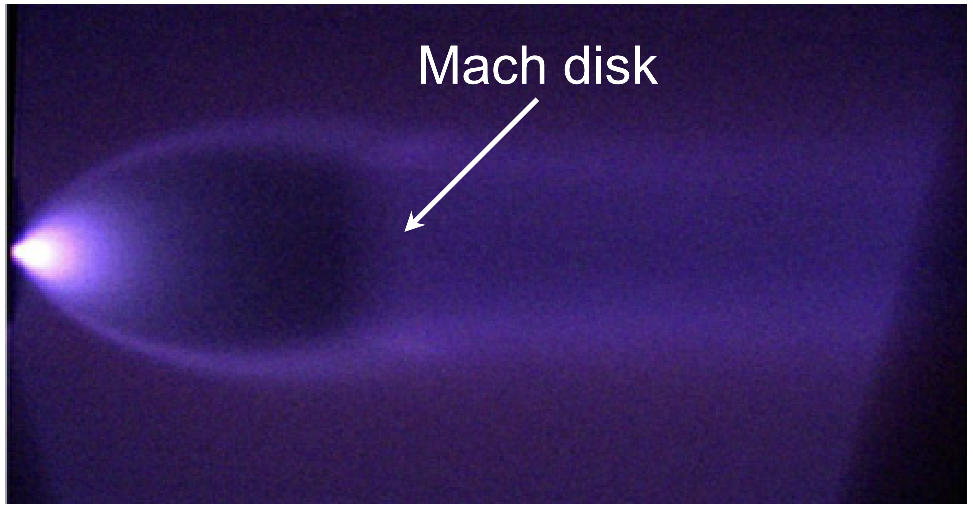


in laser spectroscopy

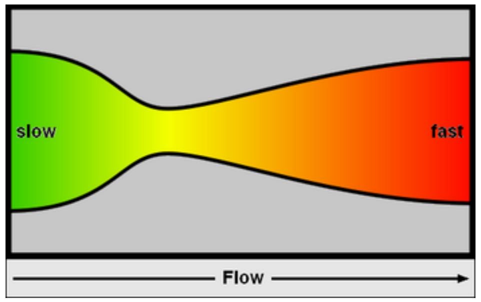
In-Gas Laser Ionisation & Spectroscopy

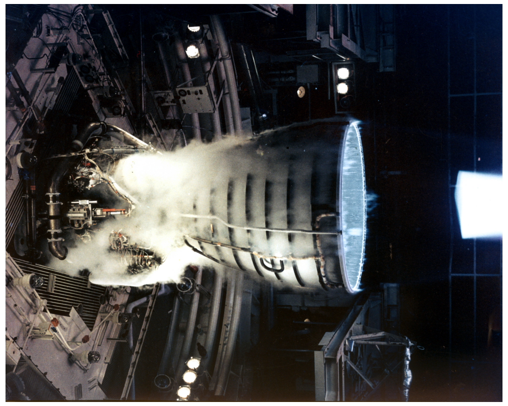
IJLIS



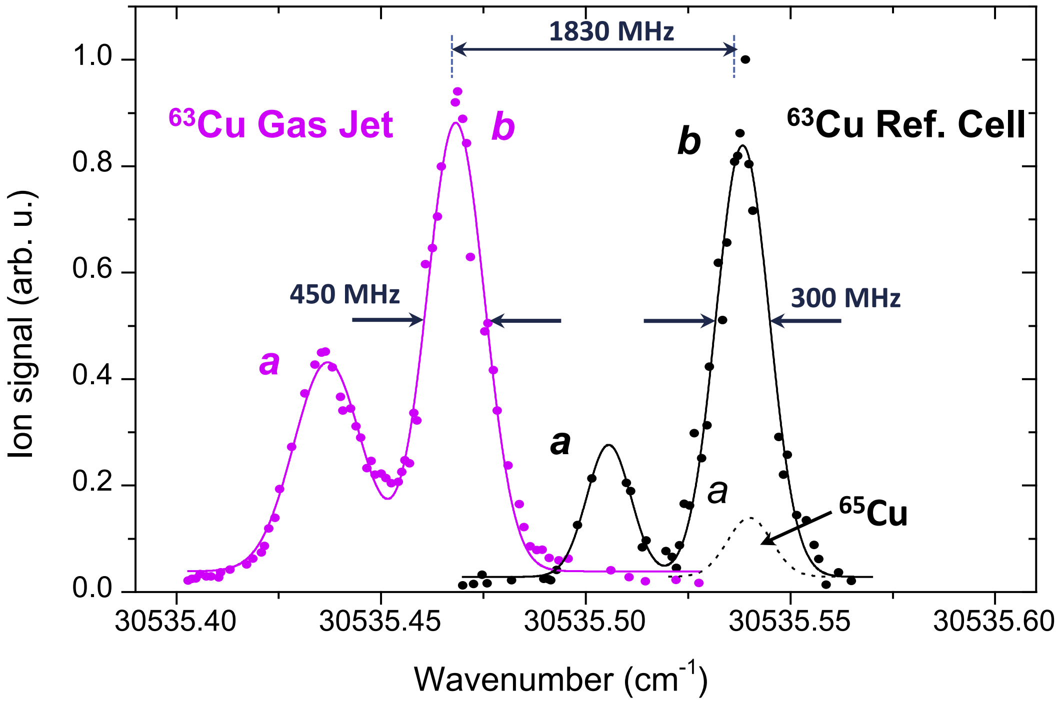


DeLaval Nozzle





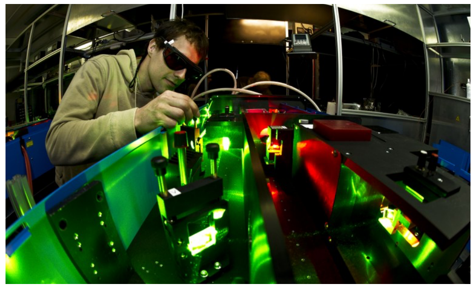
- Shaping a parallel gas jet for minimal divergence
- High Mach number for low temperature
- Cross beam geometry to probe only the jet



In-Jet Laser Ion Source

Lecture 1

- The atom is sensitive to the properties of the nucleus
    - spin, electromagnetic moments, anomalies, distributions



- The laser ion sources provide selective enhancement
    - clean beams for experiments
    - isomeric beams for detailed studies
    - laser spectroscopy for dipole moments & charge radii

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Ze END