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Laser-assisted modern nuclear physics

Lecture 2:
High-resolution laser spectroscopy
& atom traps

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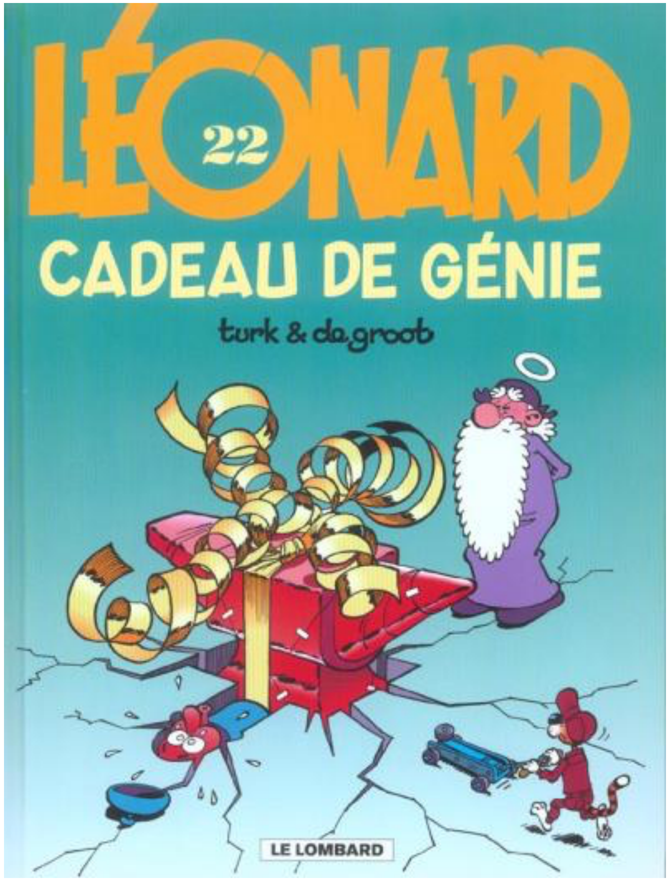
Belgium

Yes, I know!



Another Leonard

Though I might identify more with Basil sometimes…

"Je sers la science, et c'est ma joie!"

Who is Prof Thomas?

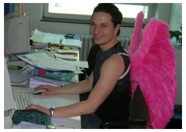
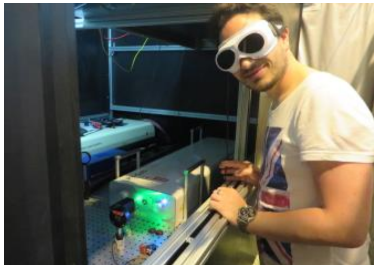
Starting 1 October 2015 as a new professor within IKS - KU Leuven

Creating new opportunities with radioactive ion beams

CERN-MEDICIS

TRANSCAT




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

High-resolution collinear laser spectroscopy

Addressing the nuclear observables across the nuclear chart

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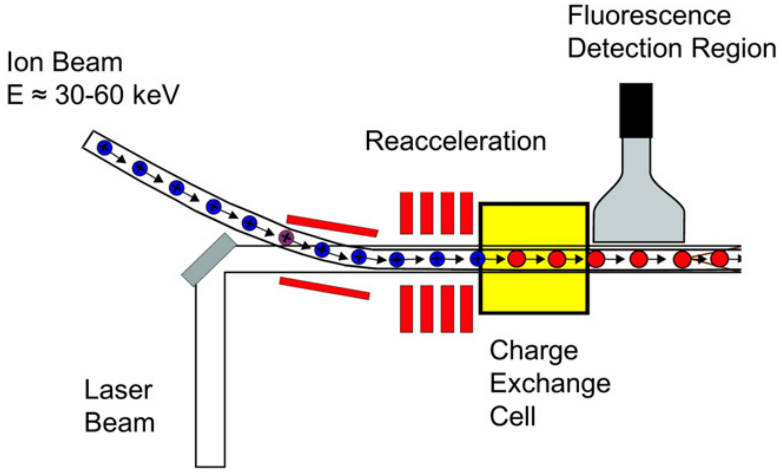
General concept: Fluorescence Spectroscopy

- Ion beam in at ISOL energy
- Tune ion beam energy
- Neutralise ions
- Overlap laser and excite atomic transition
- Observe fluorescence (atomic decay) with photomultiplier



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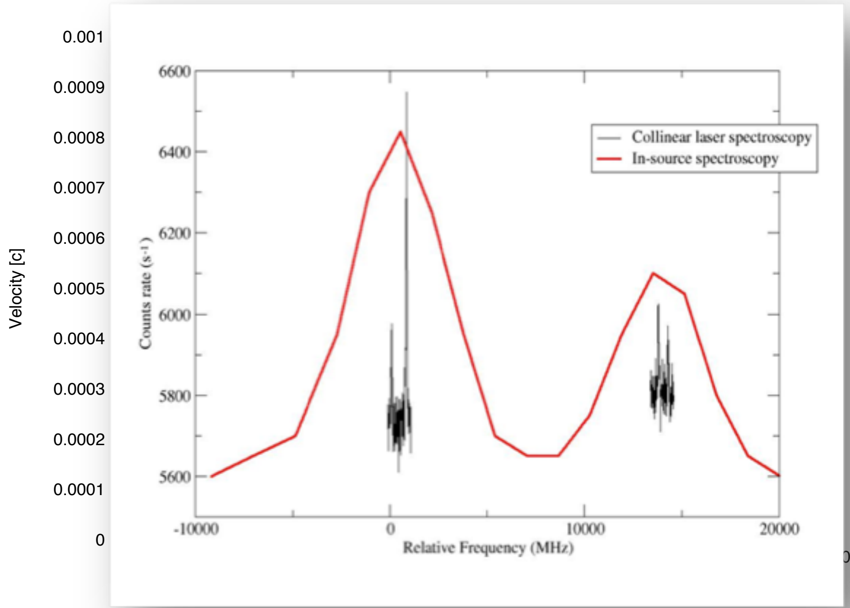
Doppler compression in collinear geometry

- The beam energy spread is determined by the ion source
  - Temperature, pressure, voltage instabilities
  - Energy spread is CONSTANT
- Transitions are broadened by the Doppler effect applied to the velocity spread of the ions
- Doppler compression

$$E = \frac{1}{2}mv^2 \Rightarrow \delta E = mv\delta v$$

Increasing *v* decreases δ*v* !!

A beam energy of 30 keV (typical at ISOL facilities) is sufficient to reduce the Doppler broadening to the natural linewidth.



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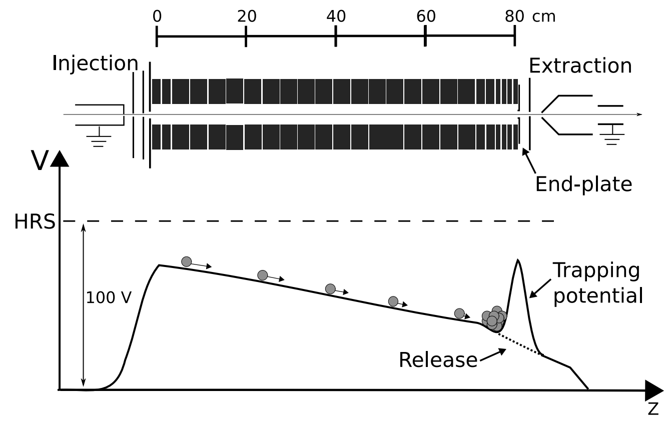
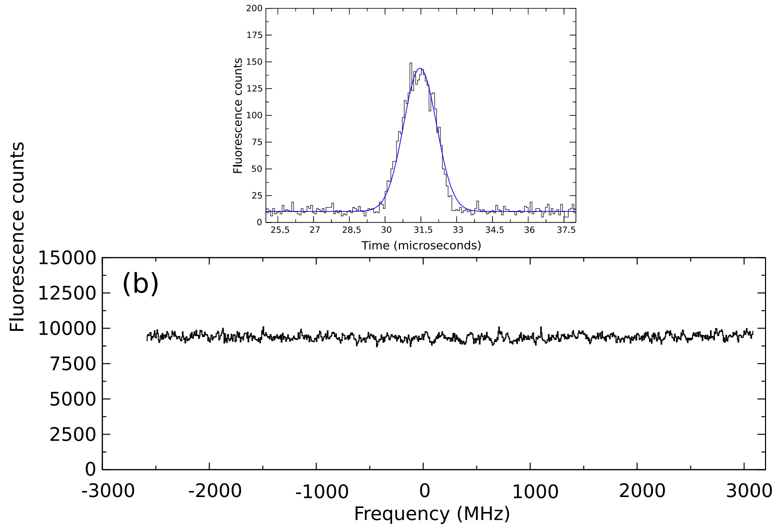
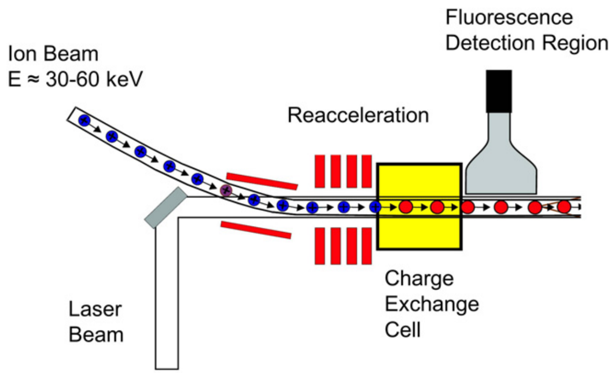
Beam bunching and time definition

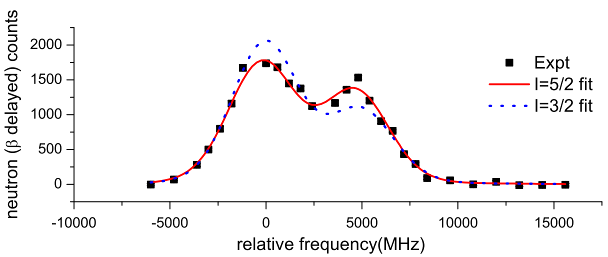
- RFQ cooler-buncher
  - collects & traps ions
  - cools them by collisions in He
  - release the ions with a well-defined time structure
- Continuous background
  - proportional reduction in background
  - no loss in signal

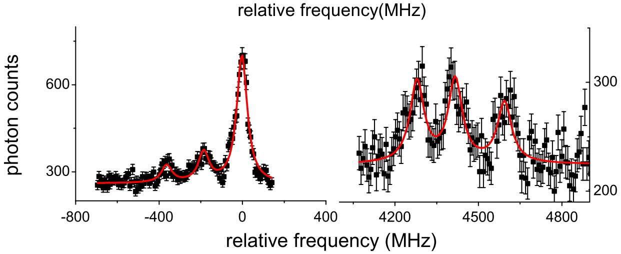




Quantum inversion in the $_{29}$Cu isotopes

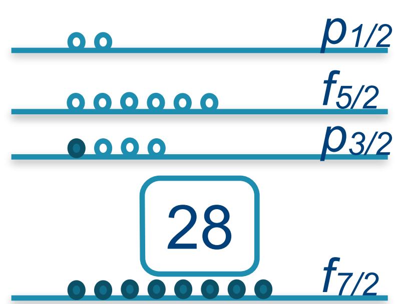


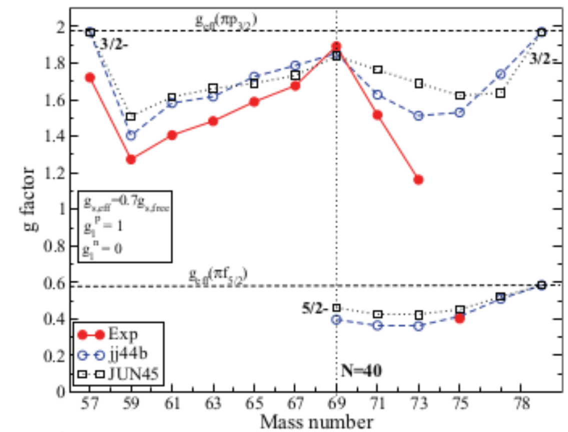


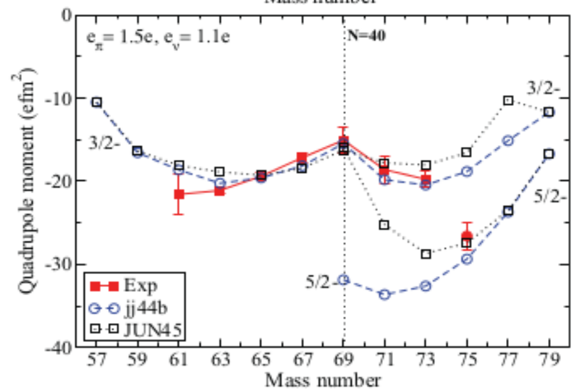


High resolution revealed the hfs, the spin, and the electromagnetic moments.

Swap between $p_{3/2}$ and $f_{5/2}$ attributed to monopole migration.

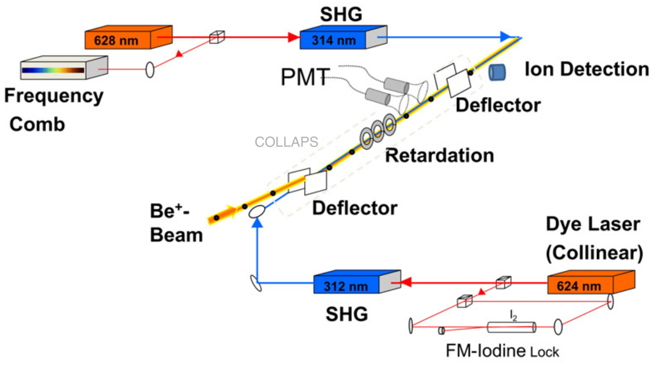


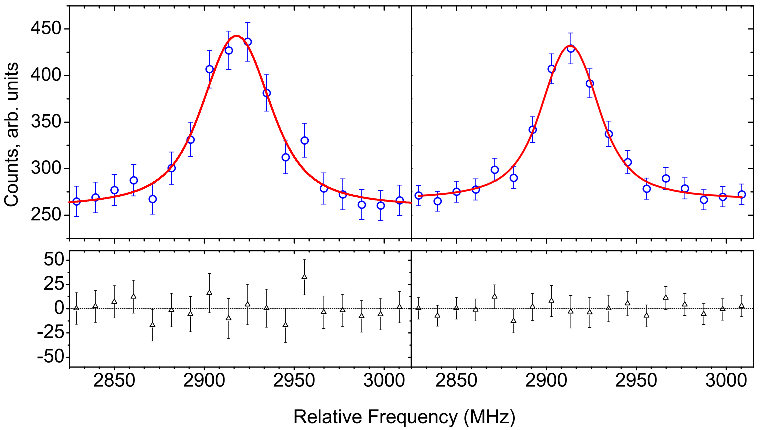




Beam energy uncertainties

- The laser frequency is Doppler corrected using the laboratory laser frequency and the beam velocity.
- Systematic uncertainties arise from the long-term drift of the laser frequency and from the jitter on the ion source high-voltage power supply.





$$\left.\begin{aligned} \nu_- &= \nu_0\sqrt{\frac{1-\beta}{1+\beta}} \\ \nu_+ &= \nu_0\sqrt{\frac{1+\beta}{1-\beta}} \end{aligned}\right\} \quad \nu_-\cdot\nu_+ = \nu_0^2$$

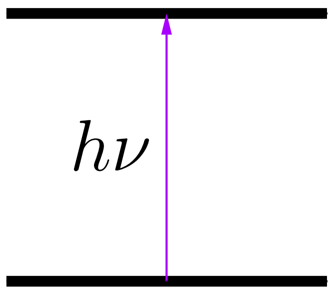
This provides an absolute measure of the laser frequency, from which one may infer the absolute beam energy.

Polarised beams

Let me remind you of yesterday…

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)

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

What about magnetic substates?!

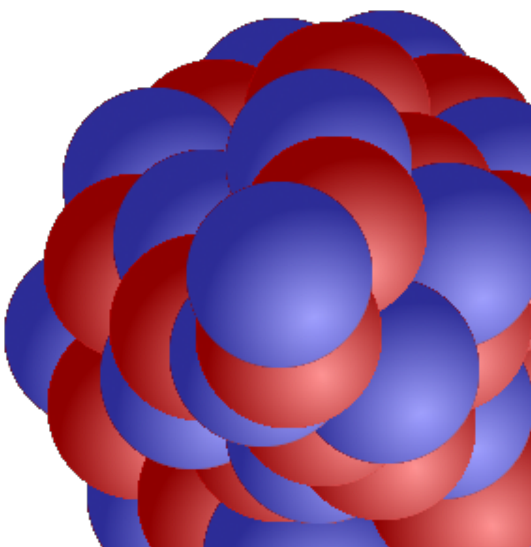
Parity change

1 unit of angular momentum

carried by the photon
=> triangular relation

Selection rules

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

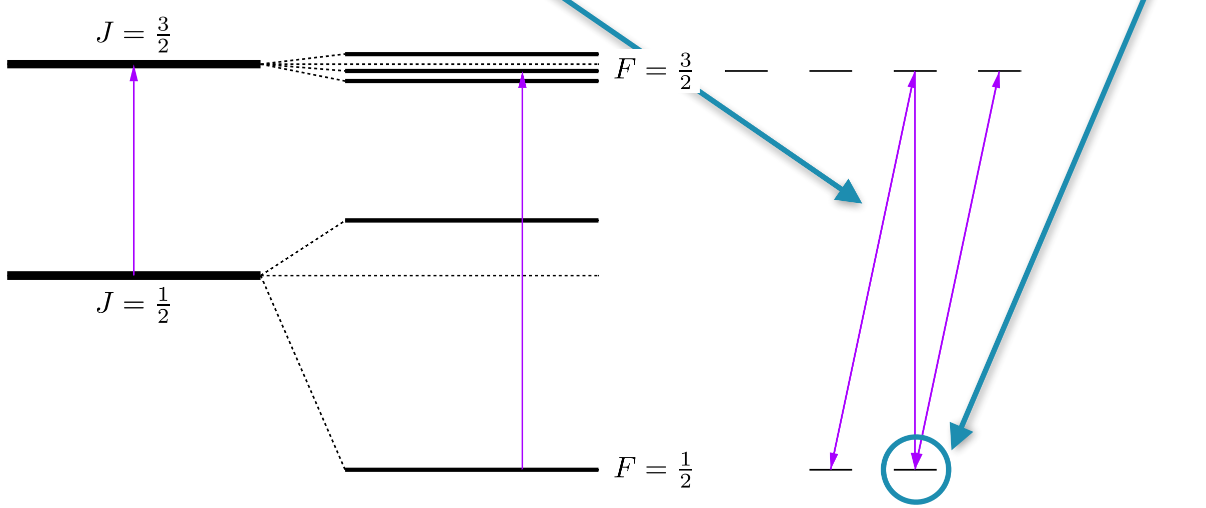


Optical pumping of magnetic substates

- The polarisation of the light provides an additional selection rule

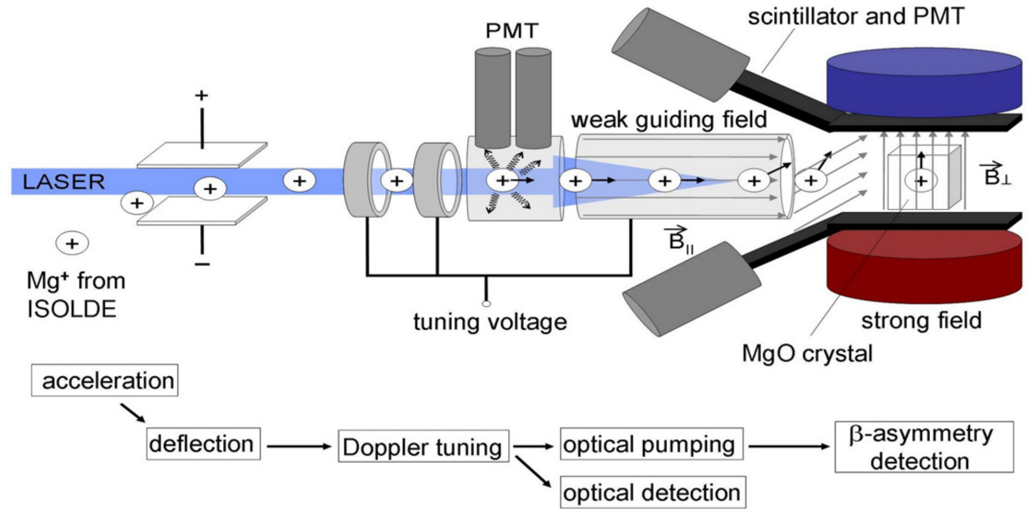
$$\text{circular+} \Rightarrow \Delta m_F = +1$$
$$\text{circular}- \Rightarrow \Delta m_F = -1$$
$$\text{longitudinal} \Rightarrow \Delta m_F = 0$$

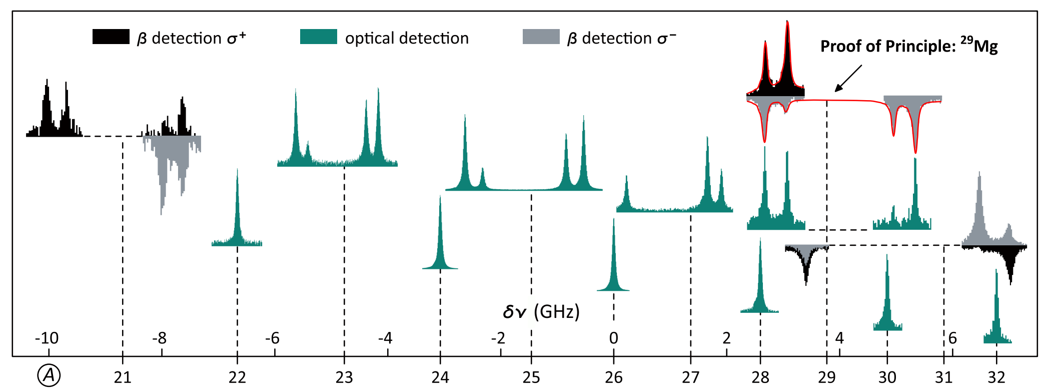
- The decay opens all three paths and eventually the population is displaced to a single magnetic substate



Polarised nuclear beams

- Under a weak laser field, the m_F substate is a good quantum number and the e^- and nucleus are coupled
- Applying a weak *B* field lines up the e^- and by proxy the nucleus
- Decay asymmetry is then be monitored



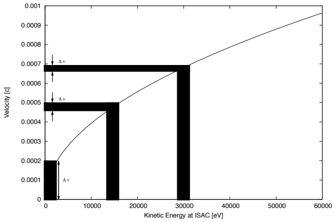


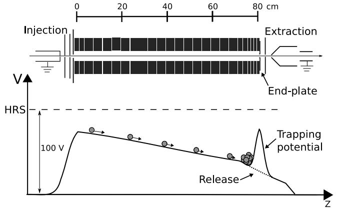
Collinear Resonance Ionisation Spectroscopy

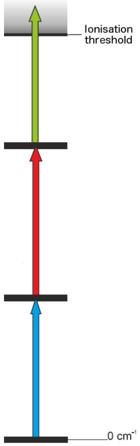
Collinear fluorescence
RESOLUTION

In-source resonance ionisation
SENSITIVITY

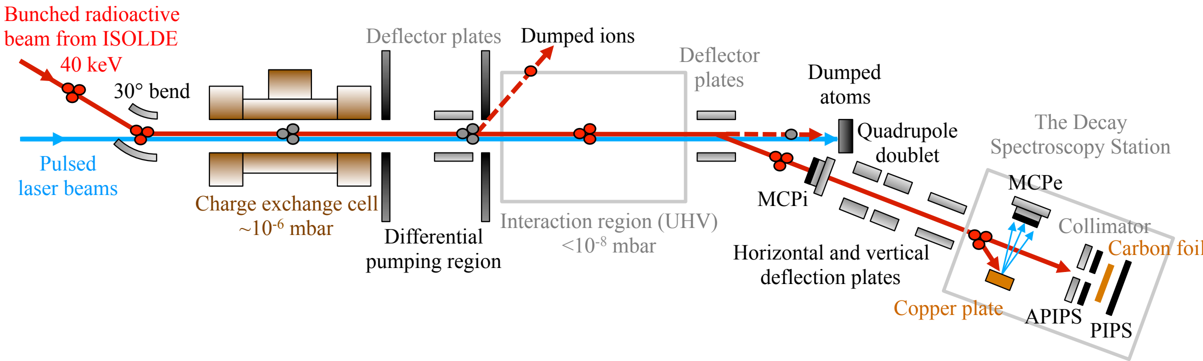
Collinear
Resonance
Ionisation
Spectroscopy

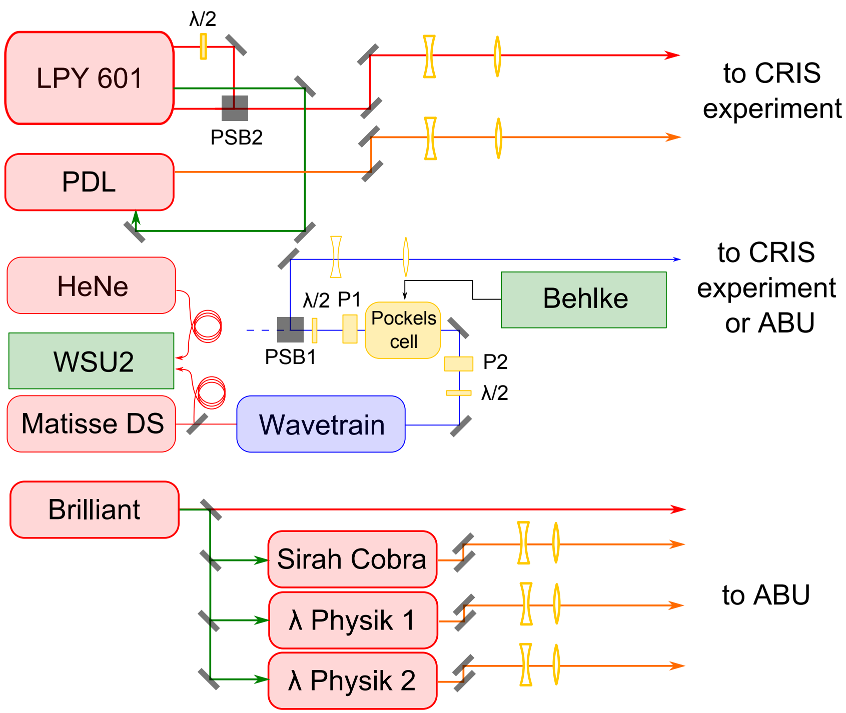


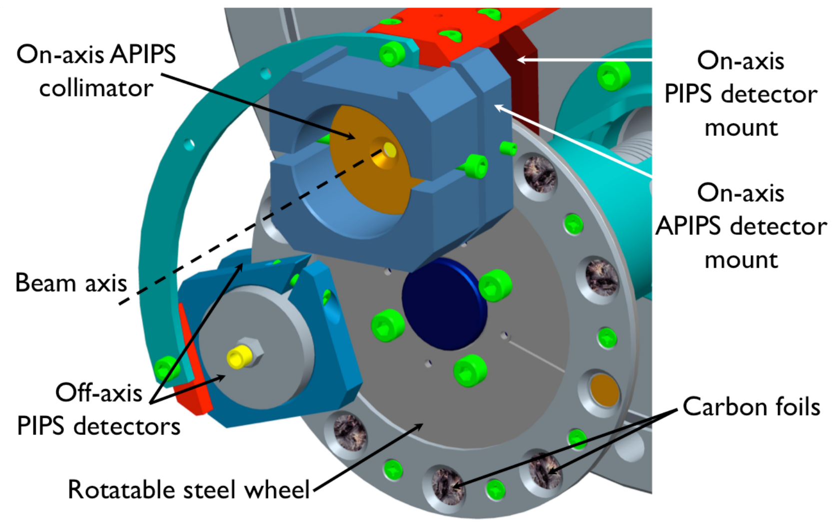




CRIS: an extra level of complication







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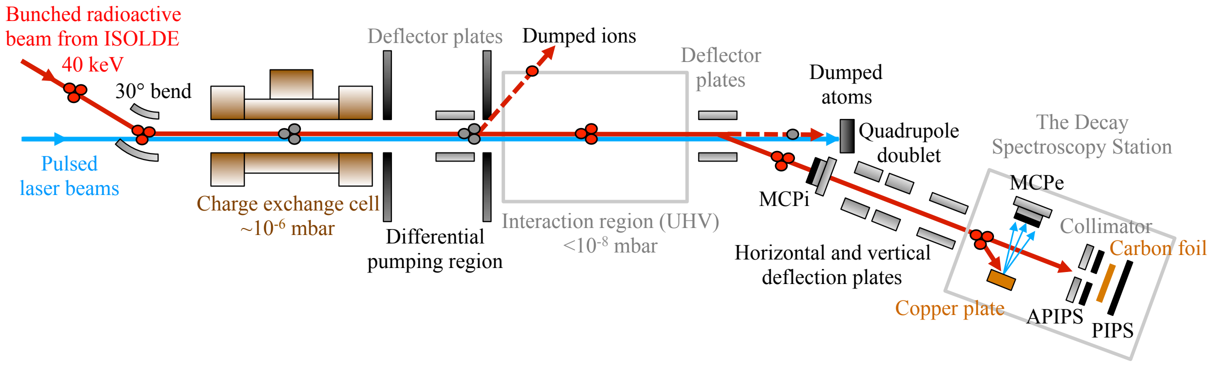
CRIS: an extra level of complication



- Starts like collinear fluorescence: 30-60 keV ion beam, neutralisation, overlap
- Ends like in-source spectroscopy: ion counting (MCPe for secondary electrons, MCPi for direct ion impact, alpha-decay spectroscopy station for short-lived nuclei)
- In-between subtleties: deflecting non-neutralised fraction, differential pumping for ultra-high vacuum against collisional non-resonant ionisation, synchronisation

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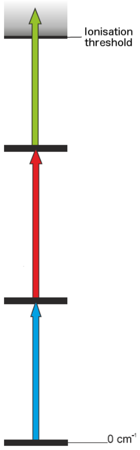
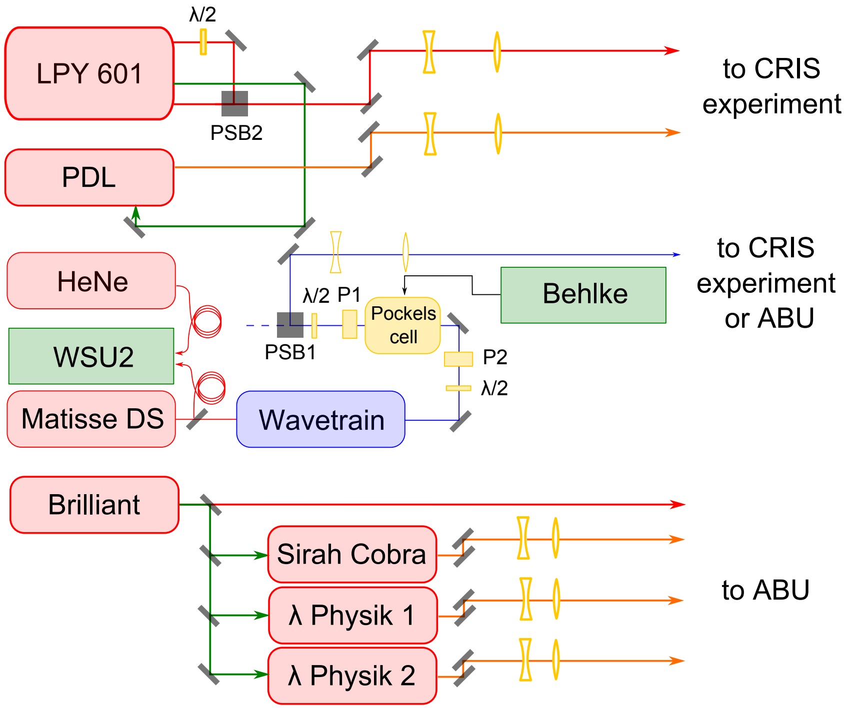
CRIS: an extra level of complication



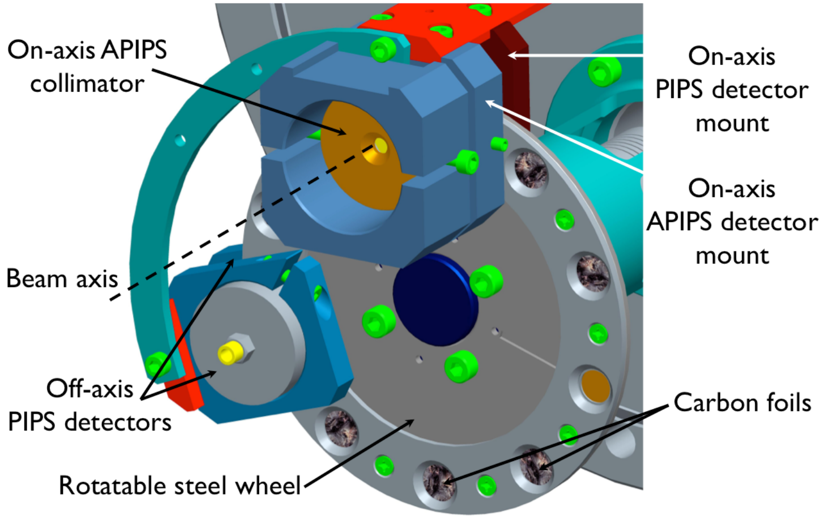
- Laser system to provide for each step in the ionisation scheme
- Resonant step for spectroscopy: high resolution is necessary => cw laser (like for other collinear work)



- Final step requires a high photon flux => high power density => pulsed laser
- Duty cycle of the ion beam delivery has to match that of the laser => RFQ bunch release & pulsed laser synchronisation

CRIS: an extra level of complication

- 3 detection setups:
  - MCPi for directly impinging ions
  - MCPe for secondary electrons from ions impinging on a copper plate
  - DSS for alpha decay of short-lived isotopes
- MCPi is more sensitive to weak rates but more fragile than MCPe, and sensitive to decays
- DSS is most sensitive and allows isomer separation, but lacks instantaneous response



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CRIS: high resolution

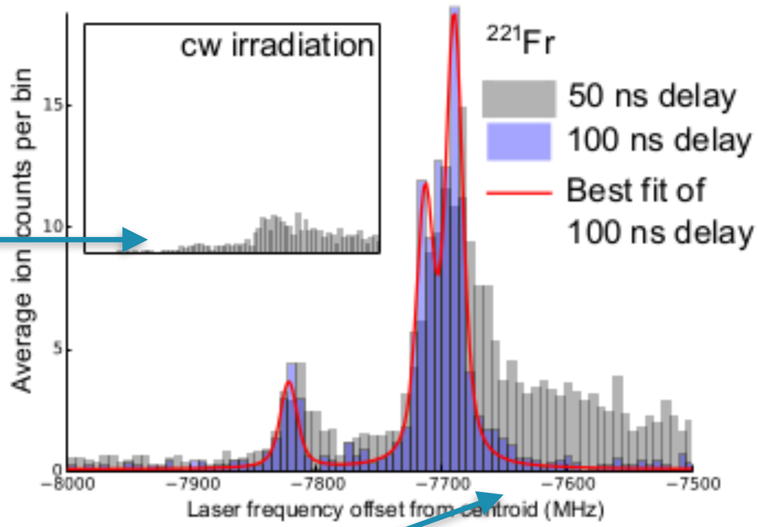
- Cw resonant laser vs pulsed ionisation laser

➡ multiple possible excitation cycles of the resonant transition and optical pumping

➡ signal loss & broadening

★ Chopped cw laser light!

- 50 ns pulse length
- synchronised with ion bunch and pulsed lasers
- delayed to avoid interference with other lasers



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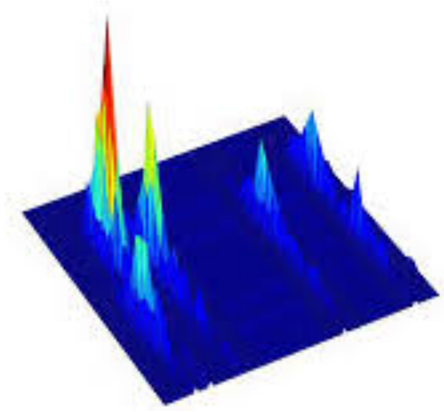
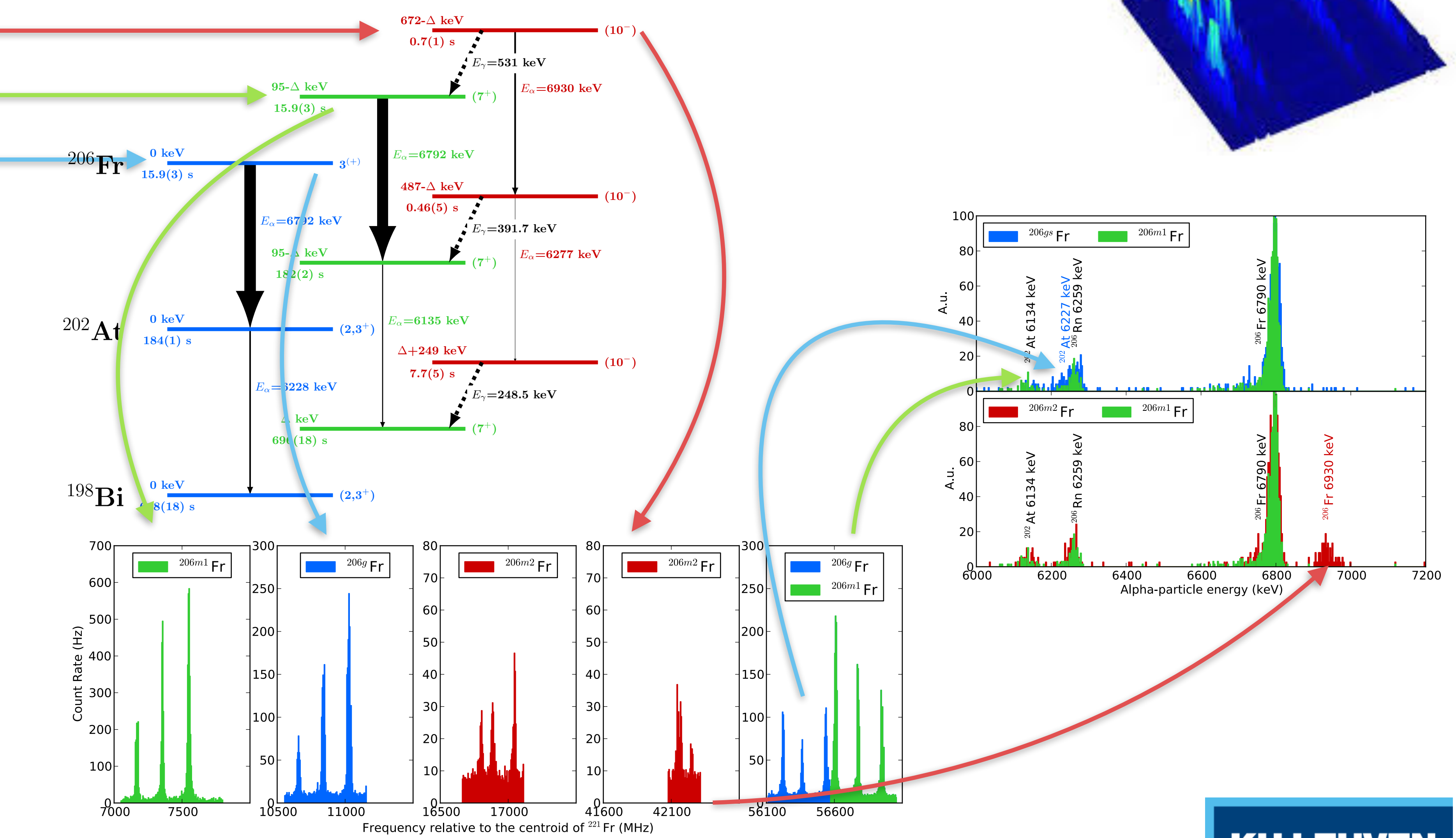
CRIS: high sensitivity





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Atom trapping

Another leap into resolution

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Laser cooling

➡ Radiative Pressure

photons give a small momentum transfer

radiation is isotropic

Irradiate - Radiate - Repeat

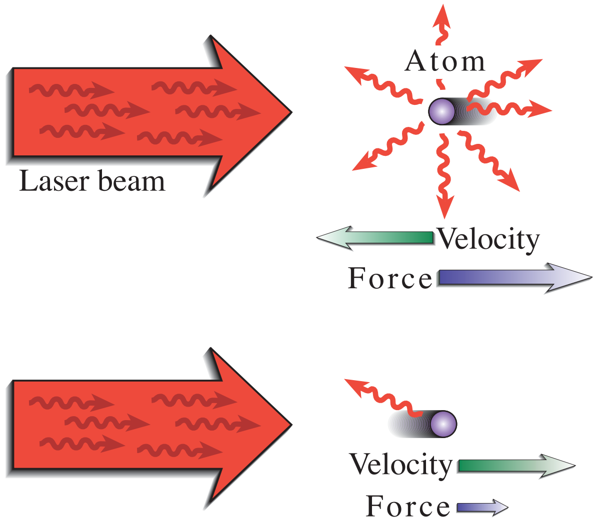
➡ Radiative Pressure Cooling

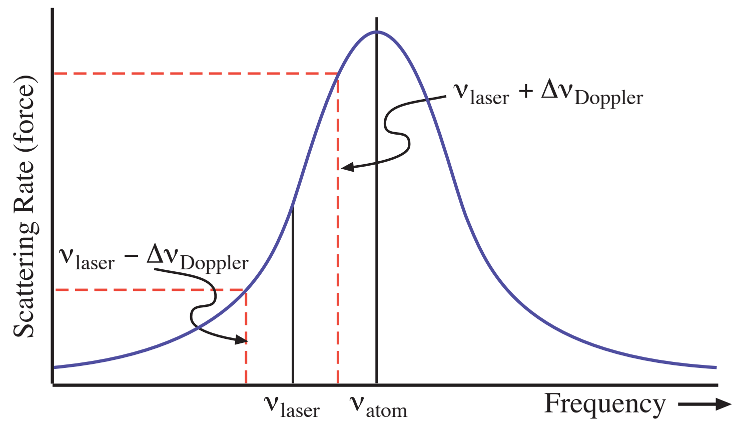
put the laser slightly off resonance

Doppler effect depending on velocity direction

velocity dependent force

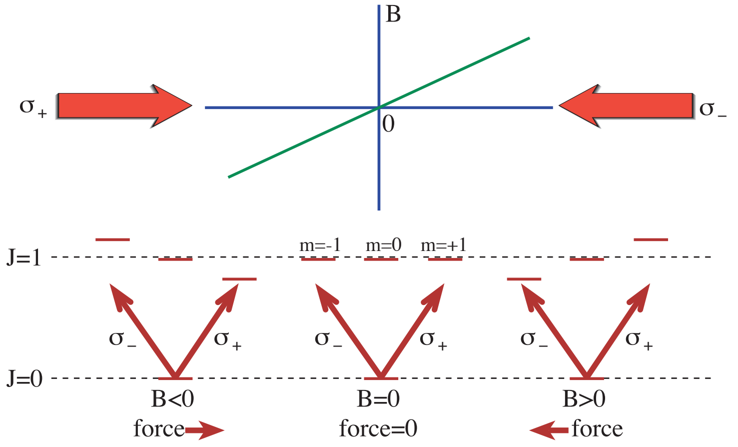
apply on all 6 directions

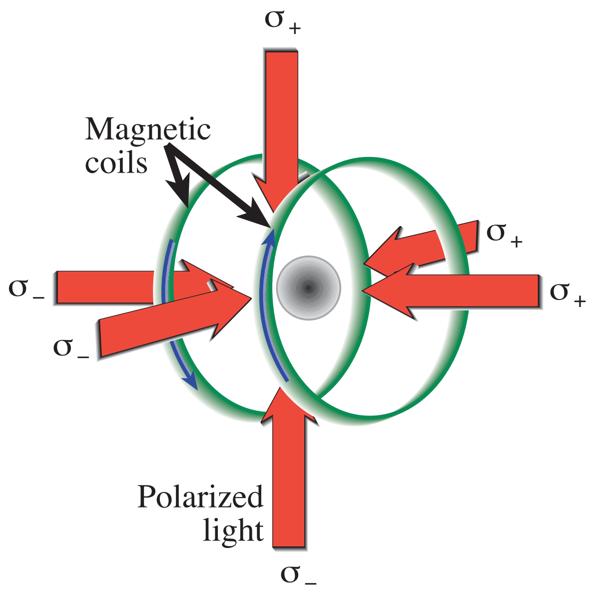




Laser trapping

- ➡ Magneto Optical Trap
  - small magnetic field to lift m_j degeneracy
  - use laser helicity to tune scattering rate
  - push in all 6 directions
- ★ You will always make an odd number of mistakes!!





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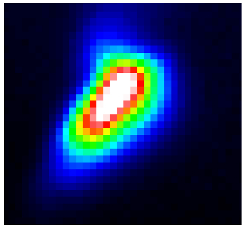
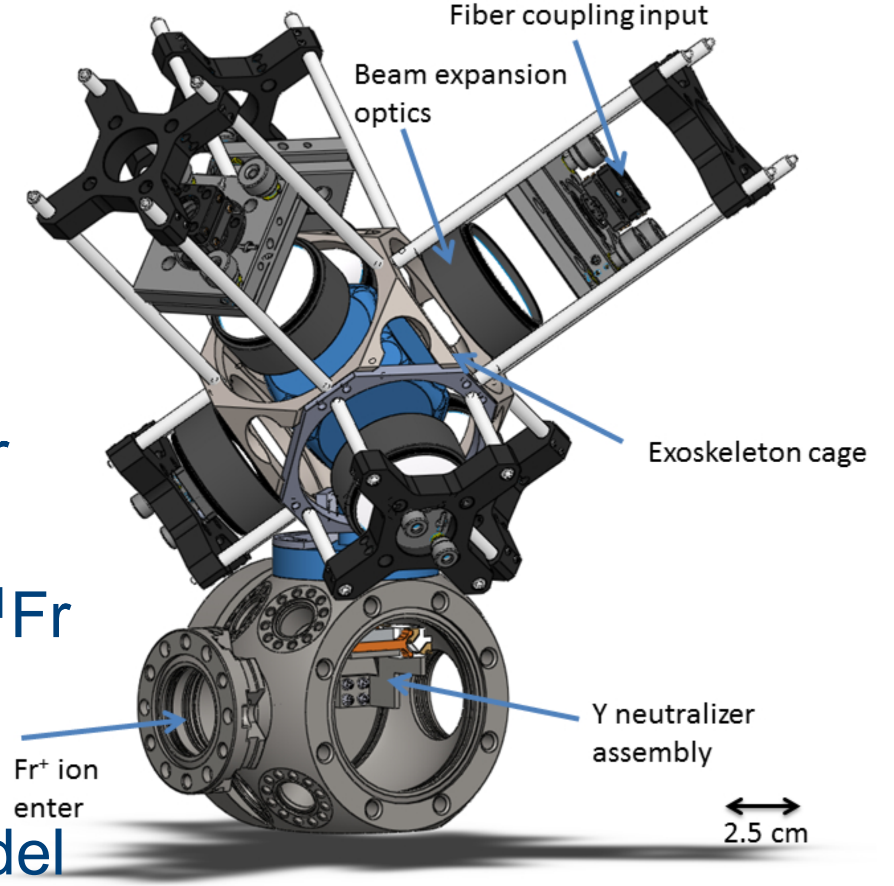
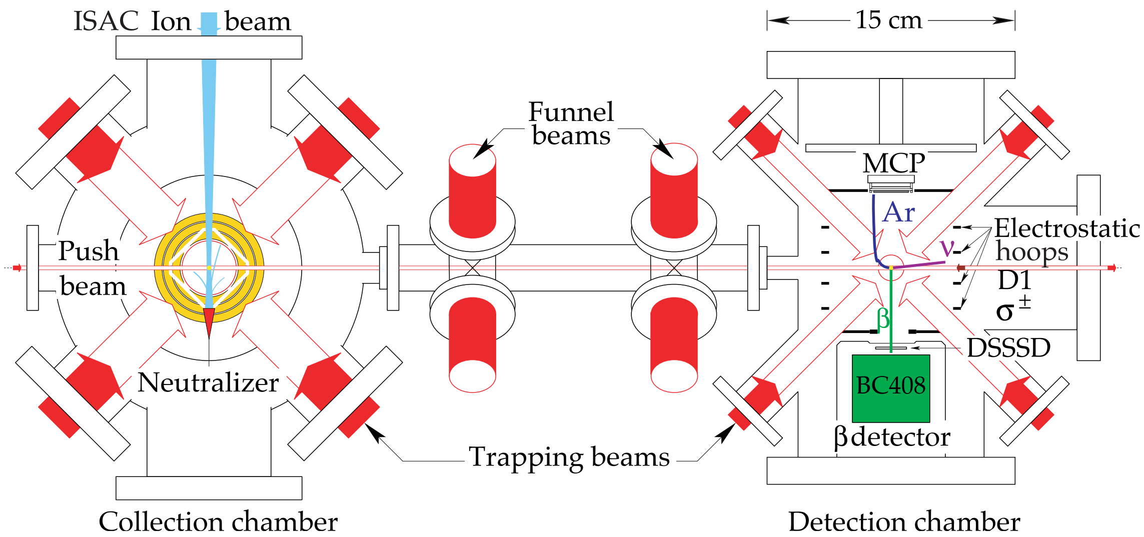
Laser Traps in Action



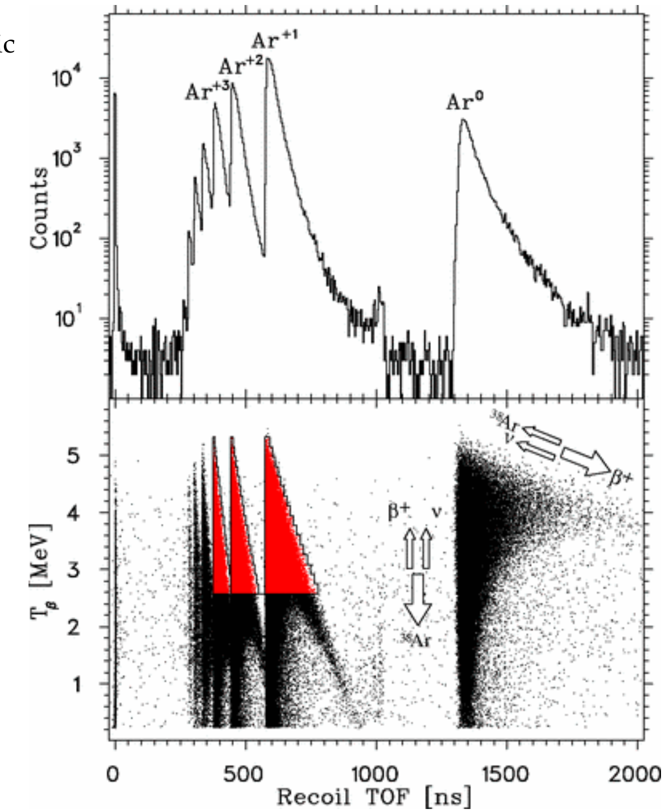
- FrPNC experiment at TRIUMF
  - successfully trapped ^{206}Fr
  - measured the hyperfine anomaly in ^{206,207,209,213,221}Fr
  - will search for anapole moments and physics beyond the Standard Model



Laser Traps in Action

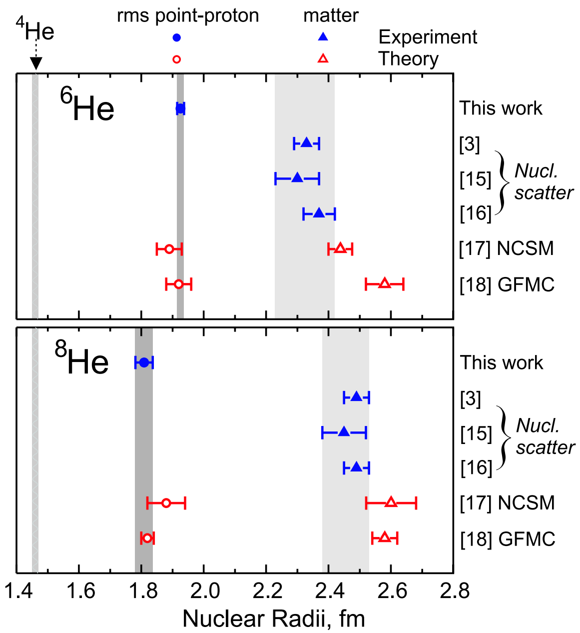


Study of the angular correlation between the electron and the neutrino in β decay



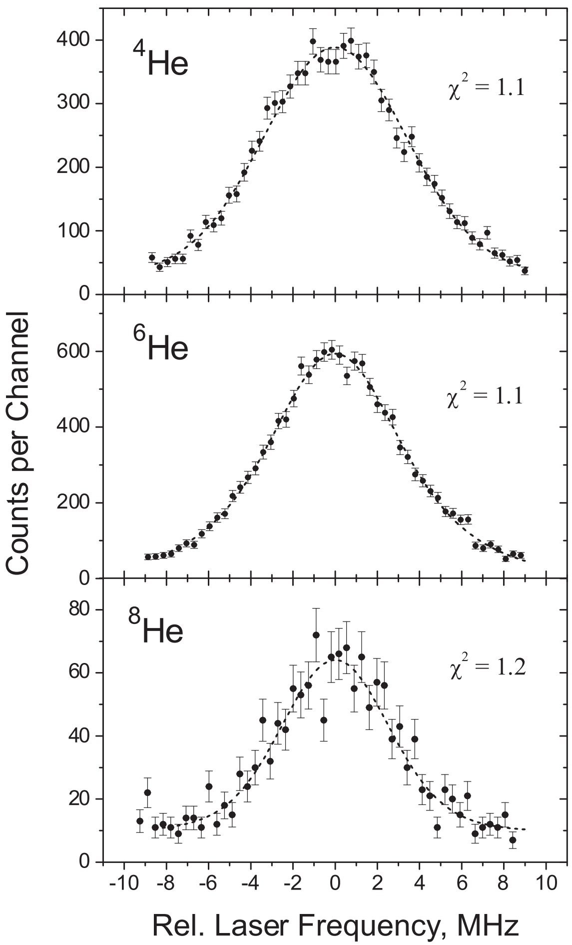
- TRINAT:
  - laser catcher
  - laser transport
  - laser trap

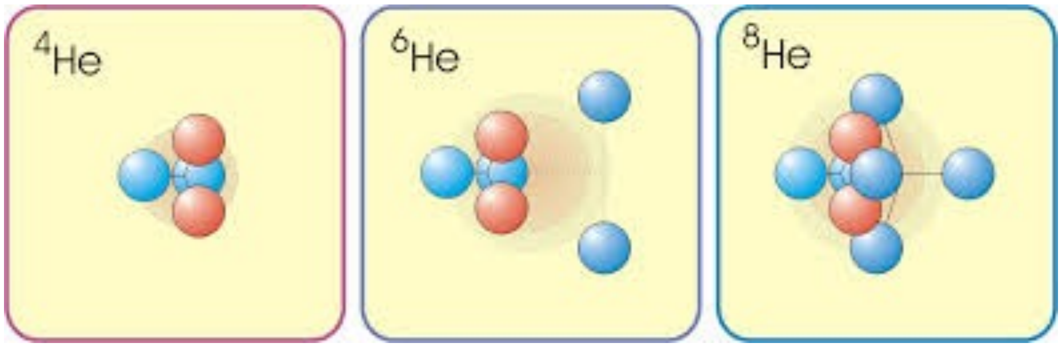
Laser Traps in Action

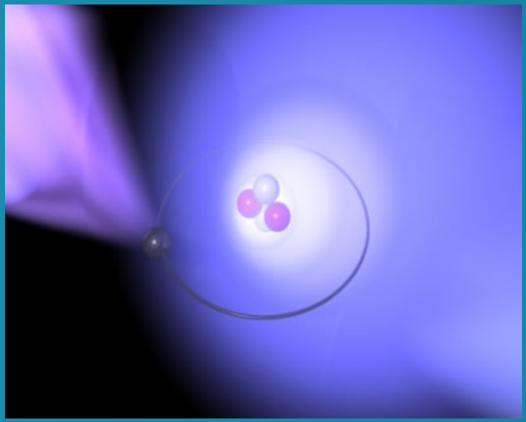


The ANL group has a large array of atom trapping capabilities.

Highlighted here is the work on the halo structure in He, performed at ANL & GANIL…







Exotic laser spectroscopy

As if radioactive nuclei aren’t exotic enough!

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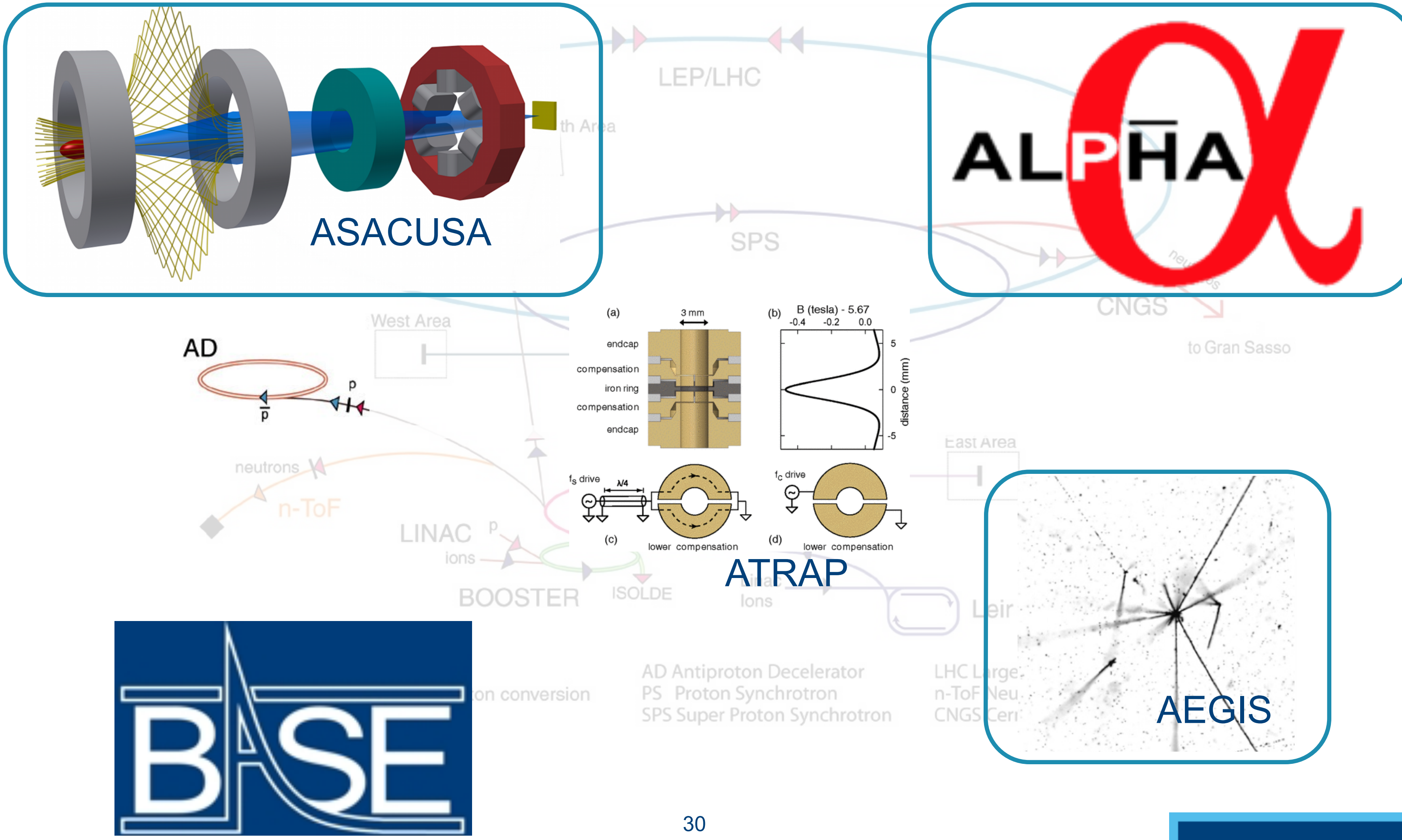
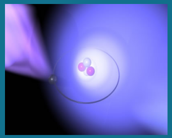
Laser spectroscopy at CERN AD



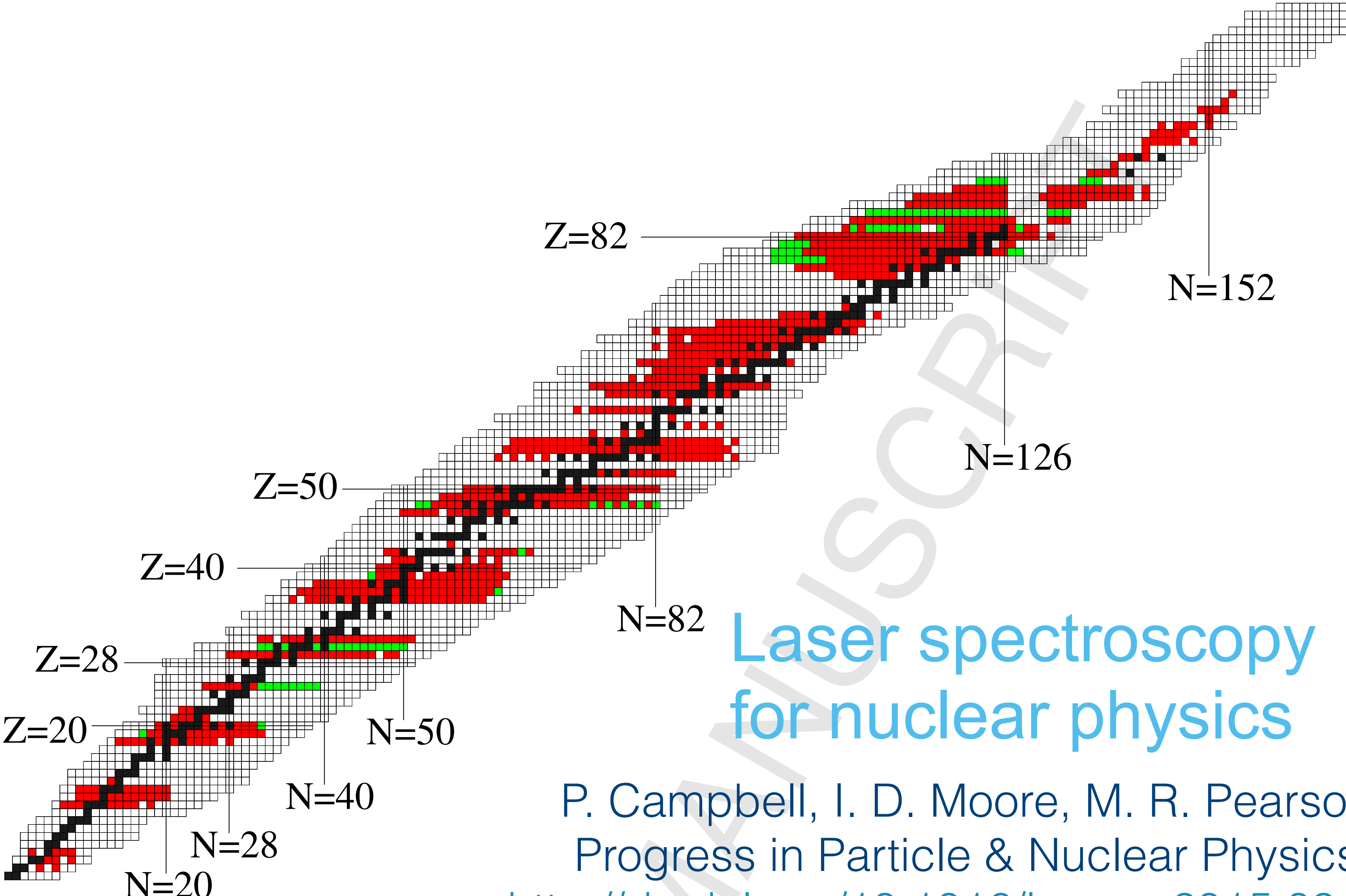
- Collinear laser spectroscopy
  - ✦ High resolution to probe the physics observable
  - ✦ High sensitivity to the equipment stability

- Collinear resonance ionisation spectroscopy
  - ✦ High resolution from collinear geometry
  - ✦ High sensitivity from resonance ionisation

- Laser trapping for highest resolution



- Laser spectroscopy to test the standard model and fundamental forces beyond nuclear physics



Laser spectroscopy for nuclear physics

P. Campbell, I. D. Moore, M. R. Pearson

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