Laser-assisted modern nuclear physics

Lecture 2:
High-resolution laser spectroscopy & atom traps

Prof. Thomas Elias Cocolios
IKS – KU Leuven
Belgium
Yes, I know!
Another Leonard

Though I might identify more with Basil sometimes…

“Je sers la science, et c’est ma joie!”
His team will look at astatine isotopes with mass numbers 193 - 220. They expect to see the nuclei change from discus-shaped at the lower mass numbers to spherical around the magic neutron number \((211)\) and then pear-shaped for the heavier isotopes. The shape changes show how the interplay between the individual and collective behaviour of nucleons (protons and neutrons) changes as the number of neutrons increases.

Being able to observe and measure these minute changes in the atomic nucleus is only possible due to the unique combination of precision instrumentation and experimental setups at ISOLDE. And that's what continues to attract UK researchers.

Faster laser

The CRIS beamline has just taken delivery of a new laser, thanks to a £40k Ernest Rutherford Fellowship grant from STFC. Manufactured by UK specialists, Litron Lasers Ltd, the new laser will enable researchers to look at shorter-lived, more exotic isotopes.

The specification for the new laser was put together by Ernest Rutherford Fellow, Thomas Cocolios (Manchester). Initially, Thomas was looking for several portable lasers that, between them, would deliver flexibility for experimental setups and the capability to capture data faster – at the moment the existing lasers allow the team to capture data every 100 ms, but the new laser will cut this to 10 ms.

Based on Litron's modular approach to building bespoke lasers, Sales Manager, Gary Newham looked at Thomas' wish list and came up with a better idea; the result is a device with two lasers that can be operated separately or together.

"Thomas wanted several lasers, but this one does everything. It's upgradeable, flexible and easy to use."

Thomas and his colleagues are clearly keen to get started with the new laser, "It's perfectly designed for physicists!" he says, pointing out the simplicity of the connection points and demonstrating how quickly it can be switched on for use.

Gary incorporated a number of features that are normally only available on fixed installation lasers including the ability to control the laser from a handheld device, or remotely via existing software.

When you're making very precise measurements, the slightest vibration can affect your data. For the new laser, that meant mounting it on INVAR rails and using a water-cooled power supply, to provide both thermal and mechanical stability. It also reduces the noise and heat dissipated to the surrounding environment. It's the first time that Litron has used a water-cooled system for a portable laser.

There are cost benefits, too. "The new laser is more versatile and cheaper than the specification that we were originally going to buy," says Thomas. Time spent designing the laser will have benefits for Litron too. "No one else makes a portable dual-beam laser quite like this," explains Gary. "This design is going to be really popular with our other customers."

The first experiment using the new laser will take place in September.

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
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
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 \( \delta \nu \)!!

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

$p_{1/2}$

$f_{5/2}$

$p_{3/2}$

$28$ $f_{7/2}$
In order to measure the laser frequency, one may infer the absolute beam energy. This provides an absolute measure of the laser frequency, from which one may infer the absolute beam energy.

\[
\begin{align*}
\nu_- &= \nu_0 \sqrt{\frac{1 - \beta}{1 + \beta}} \\
\nu_+ &= \nu_0 \sqrt{\frac{1 + \beta}{1 - \beta}} \\
\nu_- \cdot \nu_+ &= \nu_0^2
\end{align*}
\]
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 (En)

\[ \Delta l = \pm 1 \]
\[ \Delta J = 0, \pm 1, \quad J = 0 \Rightarrow 0 \]
\[ \Delta F = 0, \pm 1, \quad F = 0 \Rightarrow 0 \]

Parity change

1 unit of angular momentum

carried by the photon

\[ \Rightarrow \text{triangular relation} \]

Selection rules

\[ s \leftrightarrow p, \quad p \leftrightarrow d, \quad d \leftrightarrow f, \ldots \]
Optical pumping of magnetic substates

- The polarisation of the light provides an additional selection rule

  - circular+ $\Rightarrow \Delta m_F = +1$
  - circular$- \Rightarrow \Delta m_F = -1$
  - 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

- 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
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
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
CRIS: high sensitivity

\[ E = 6792 \text{ keV} \]

\[ E = 6930 \text{ keV} \]

\[ E = 6228 \text{ keV} \]

\[ E = 6135 \text{ keV} \]

\[ E = 6277 \text{ keV} \]

\[ 198 \text{Bi} \]

\[ 206 \text{Fr} \]

\[ 202 \text{At} \]

\[ 0 \text{ keV} \]

\[ 0 \text{ keV} \]

\[ 0 \text{ keV} \]

\[ 0 \text{ keV} \]

\[ 15.9(3) \text{ s} \]

\[ 184(1) \text{ s} \]

\[ 618(18) \text{ s} \]

\[ 696(18) \text{ s} \]

\[ 182(2) \text{ s} \]

\[ 69(18) \text{ s} \]

\[ 66(18) \text{ s} \]

\[ 7.7(5) \text{ s} \]

\[ 184(1) \text{ s} \]

\[ 15.9(3) \text{ s} \]
Atom trapping

Another leap into resolution
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!!
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

Figure 3. Prototypical TRIUMF Neutral Atom Trap 2-MOT apparatus. A vapor-cell MOT traps radioactives with 0.1% efficiency, and then the atoms are transferred with high efficiency to as eco condition detectors. An uniform electric field collects recoils to a microchannel plate (MCP), where their position and time-of-flight (TOF) with respect to the $\beta^+$ is measured. An additional beam ('D1 $\sigma^\pm$') can spin polarize the atoms by optical pumping when the MOT is off.

Trapping beams

Detection chamber

Funnel beams

Collection chamber

Neutralizer

Push beam

ISAC Ion beam

\begin{itemize}
  \item **TRINAT:**
  \begin{itemize}
    \item laser catcher
    \item laser transport
    \item laser trap
  \end{itemize}
\end{itemize}

Study of the angular correlation between the electron and the neutrino in $\beta$ decay
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!
Laser spectroscopy at CERN AD

ASACUSA

AEGIS

ALPHA

ATRAP
• 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
Progress in Particle & Nuclear Physics
http://dx.doi.org/10.1016/j.ppnp.2015.09.003
published online 30 September 2015
Ze END