Developments towards Doppler-free in-source laser spectroscopy at ISOLDE RILIS

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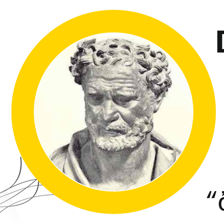
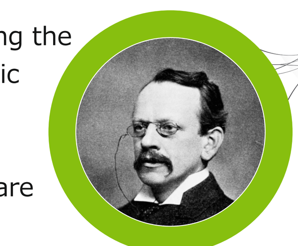
PHYSICS PREREQUISTIES

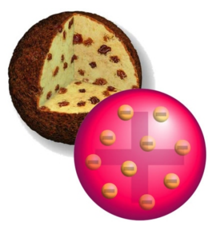
THE ATOMIC THEORY

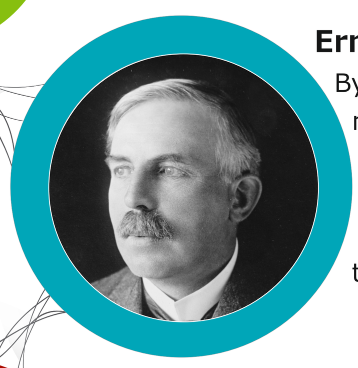


Democritus (460-370 BC)
"The universe is composed of two elements: the atoms and the void in which they exist and move."
First to introduce the notion of the atom : ἄτομον
"ἄ" for "not" and "τομον" for "slice" - "uncuttable", "indivisible"

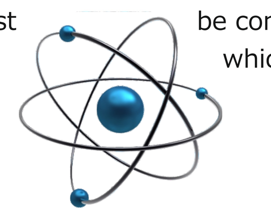


Joseph John Thompson (1897)
Discover experimentally the electron by deflecting the output ray of cathodes with electric and magnetic fields. These measurements provided the first estimation of the mass of the electron. He proposed a model of the atom where electrons are surrounded by a cloud of positive charge, like a plum pudding



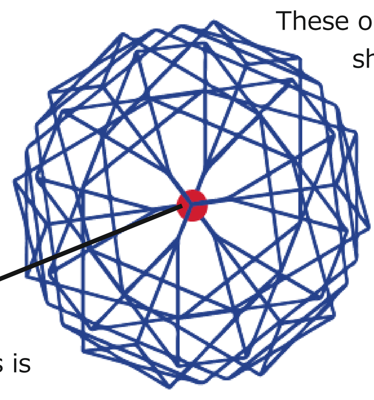


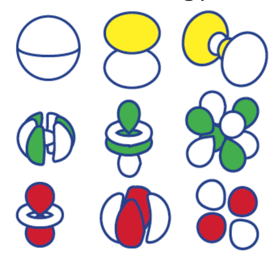
Ernest Rutherford (1912)
By bombarding Mica foils with alpha particles and measuring deflection angles above 90°, leads to the conclusion that all the mass and positive charge of the atom must be confined in a small shell around which "gravitate" the electrons.



Quantum Physics (XXth century)
With experiments like the ones performed by Stern and Gerlach, the quantum nature of the atom was revealed in further details. The first mass spectrometry experiments revealed the existence of the neutron. Today, we conceptualize the atom as a cloud of electrons surrounding a small nucleus, composed of protons and neutrons.

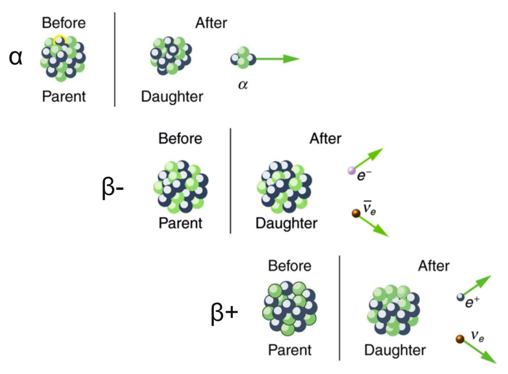
- Different shapes, or "orbital" of the electron cloud, depending on the electron energy
- These shapes (1) represents the probability to find the electron at a certain position.
- The energy can only take discrete values: it is Quantized. These orbitals can be conceptualized as shelves, called "energy levels" that can host only a limited amount of electrons, the higher the shelf, the higher the electron energy.





(1)

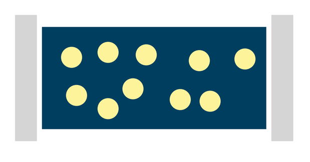
- The atomic nucleus is contituted of protons and neutrons.
- The number of protons is different for each element, the number of neutrons can vary.
- An element with a different number of neutrons is called an **"isotope"**.
- Isotopes can be unstable, in which case, the can spontaneously emit different particles to reach a stable state. This process is called **"radioactive decay"** . It can be of three types : Alpha, Beta and Gamma (2)



(2)

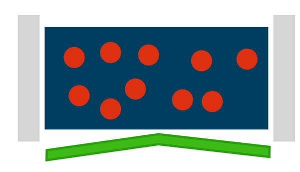
LASER

The LASER (Light Amplification by Stimulated Emission of Radiation) phenomenon is due to the unique property of excited atoms, that when interacting with photons are more likely to emmit another photon with the same properties (Energy, phase,direction…) as the first one. If trapped between mirrors, these photons will be able to acheive several passes in the "amplification medium", each time "stimulating" the production of the same photons. Then, if one of the mirrors, called the "output coupler", is partially reflective or can become transparent when a voltage is applied to it, the Light that was Amplified by Stimulated Emission of Radiation (or LASER) will exit the cavity, thus producing the laser beam.



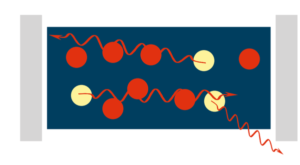
○ Atoms in ground state

When the laser is off, most of the atoms of the amplification medium are in the ground state

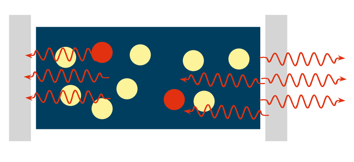


● Atoms in excited state

When the laser is on, a pump (other laser; electric field, flashlamp) is applied, such as more atoms are in excited state than in ground state, this is called **population inversion**

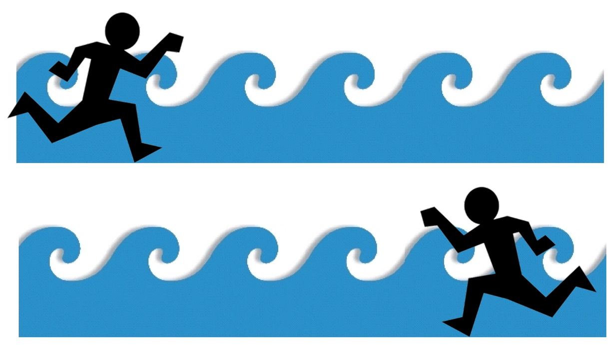


Several atoms spontaneously relax, their photons are trapped between the mirrors



These can then interact with neighbouring excited atoms. They are more likely to emmit an other photon with the same properties (Energy, phase,direction…) as the first one.

THE DOPPLER EFFECT

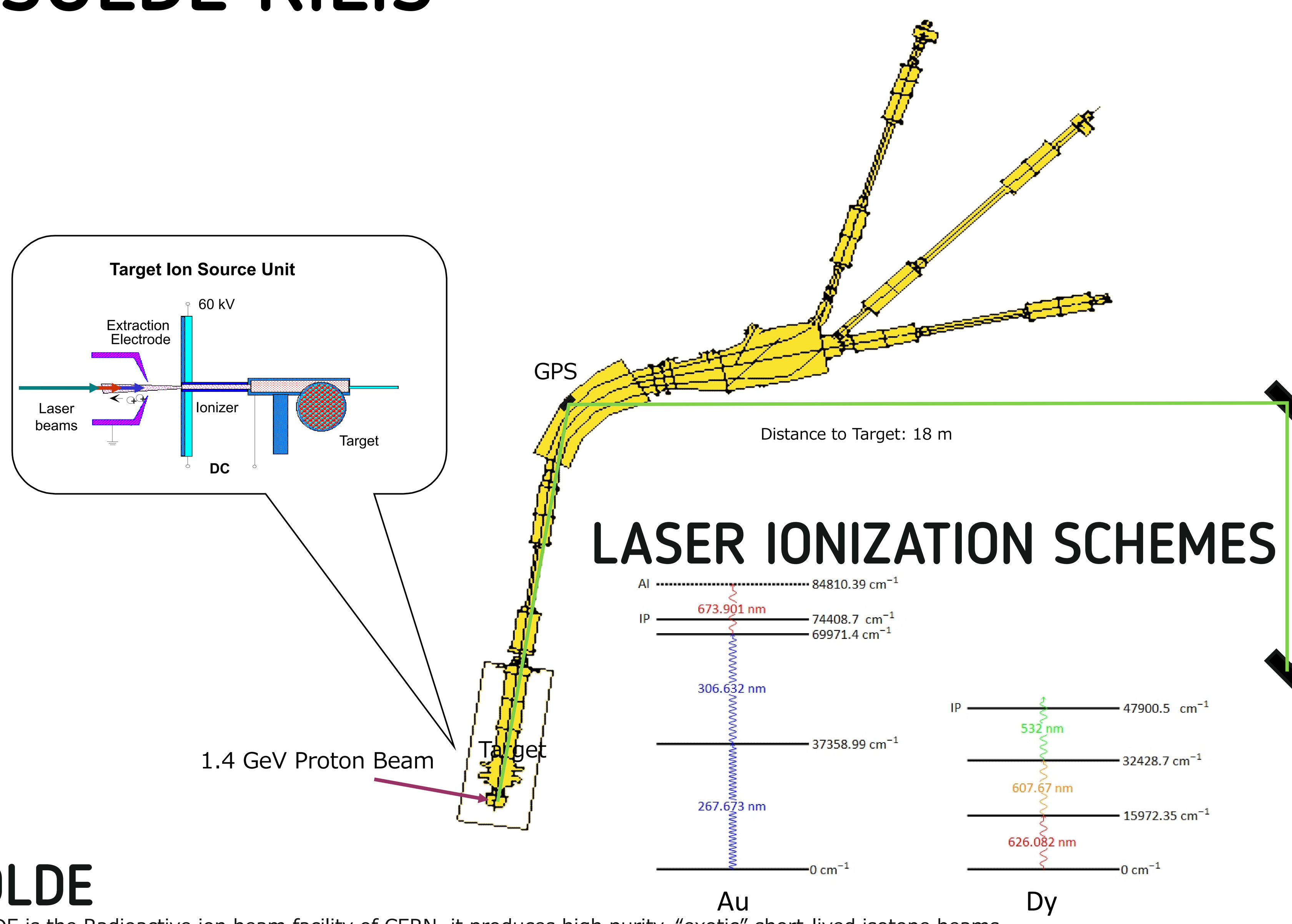


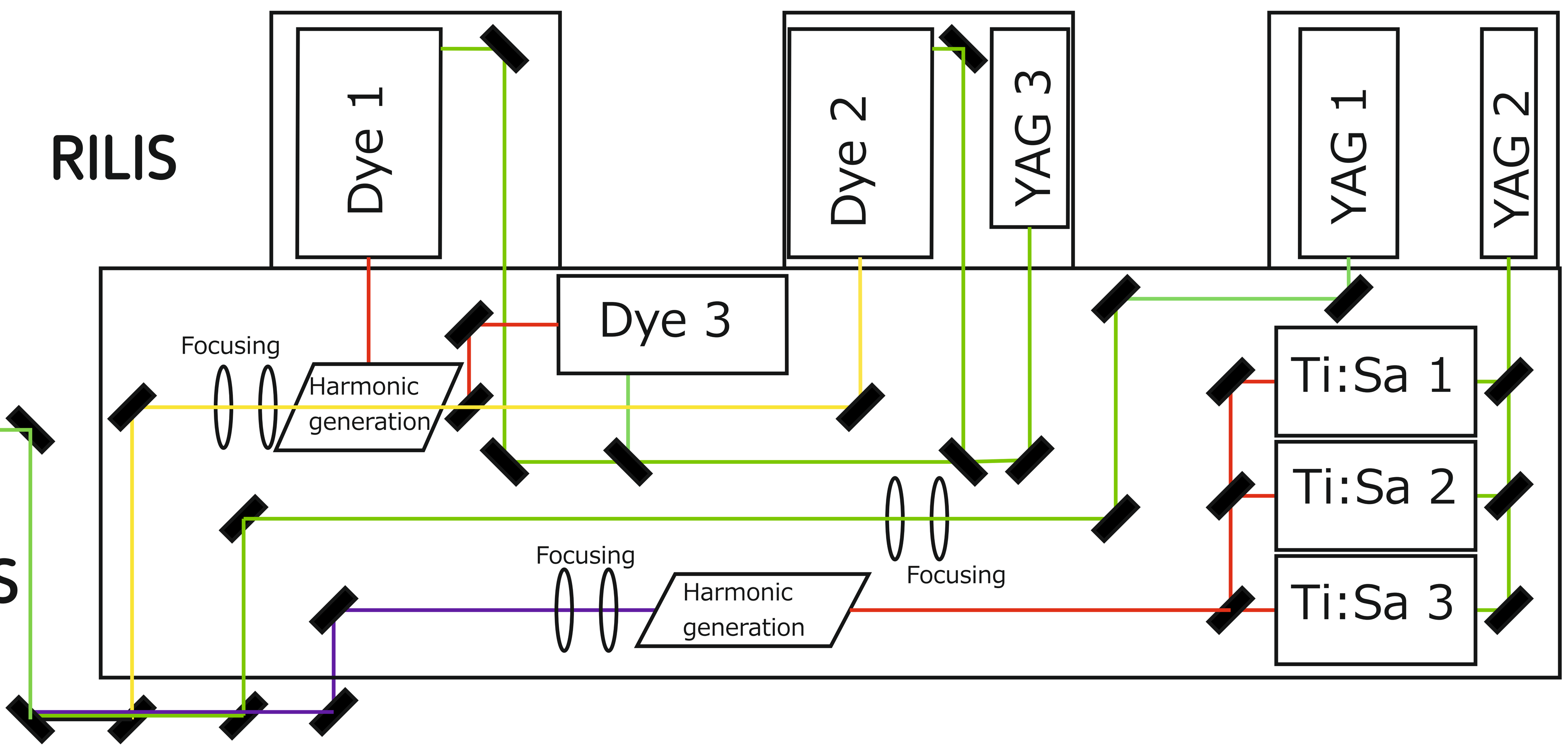
Let us consider a person on a beach, waves reaches his feet every ten seconds. If this person then runs towards the open sea, in his frame of reference, the frequency at which he receives the waves will increase let's say, every six seconds. Similarly, if the person turns around and runs towards the shore, the waves will strike him at a lower frequency, let's say every 15 seconds. The same principle applies if the source is moving. This phenomenon is called the **"Doppler effect"**, and also takes place when atoms move relative to light waves. The broadenning of the atom velocities causes a shift in their energy due to the Doppler effect. Since the atoms velocity is linked to the temperature,t he hotter the bunch of atoms, the faster is their velocity and the wider is the Doppler broadening.

At ISOLDE, the ion source is heated (~2000-2300K) which increase the Doppler broadenning of the atomic lines. As a consequence, like when an image gets blurred if the focus is changed, the Doppler effect will "blur" the information about the atomic properties.

The study of the energy levels can provide various informations about the properties of atoms and molecules (size, spin, mass etc...)

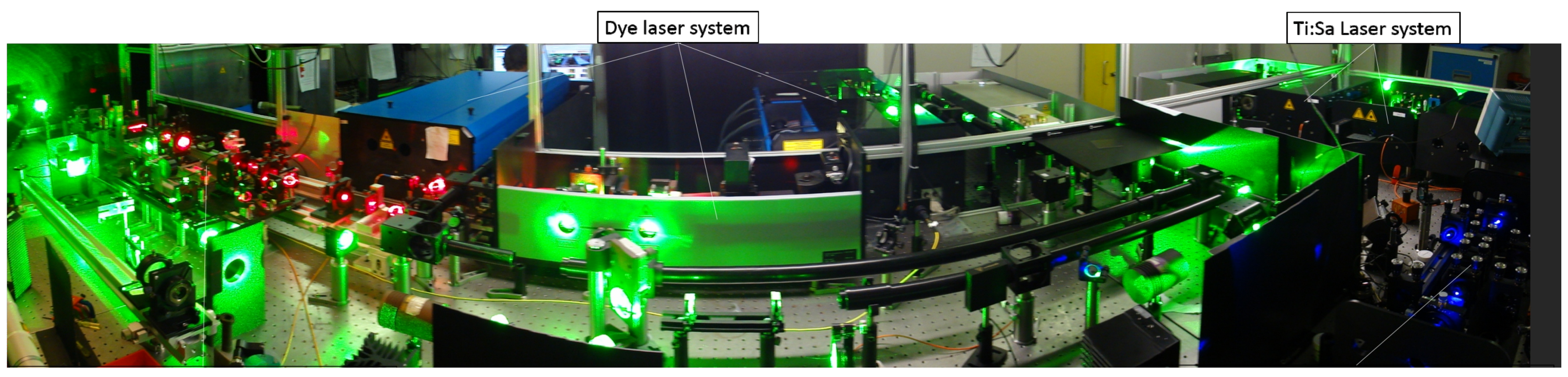
ISOLDE RILIS





LASER IONIZATION SCHEMES

RILIS (Resonance Ionization Laser Ion Source) is the most element-selective and most common ion source used at ISOLDE. The technique is based on a multi-step resonnance photo-absorption, using from two to four different laser beams from tuneable lasers (Dye and/or Ti:Sa lasers).

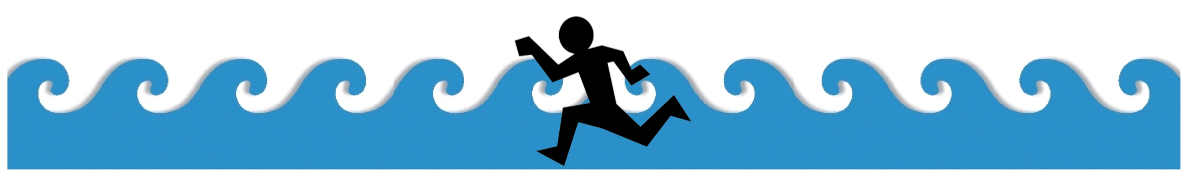


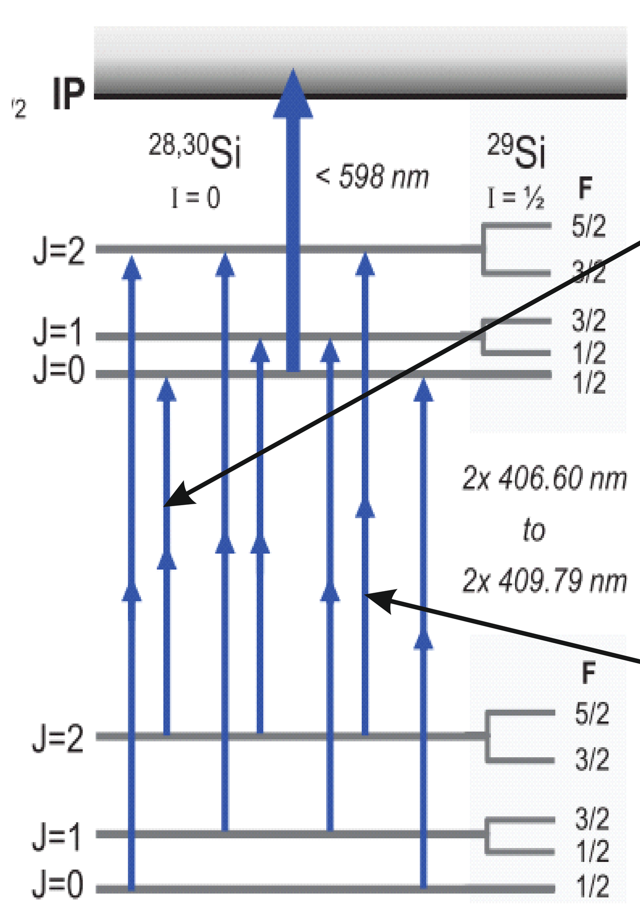
ISOLDE

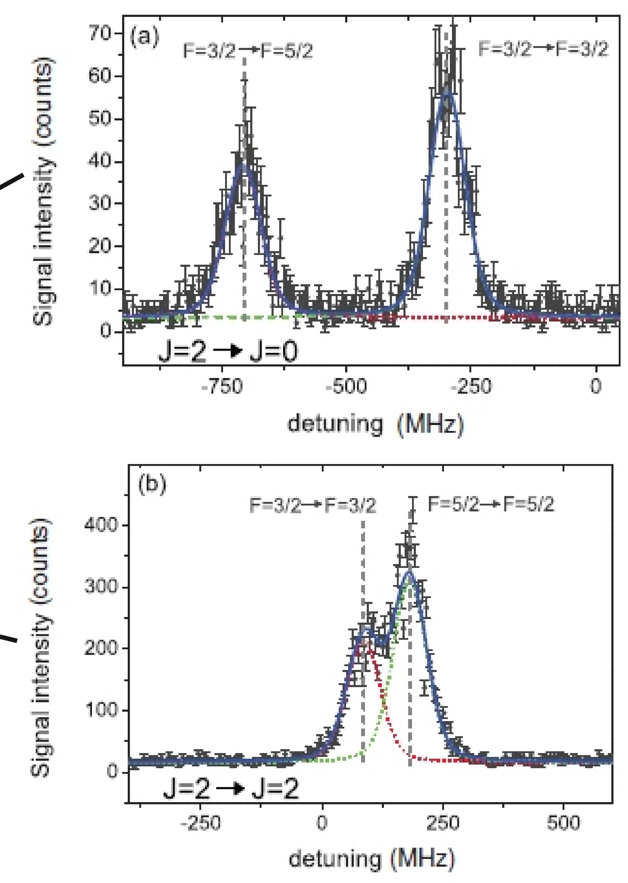
- ISOLDE is the Radioactive ion beam facility of CERN, it produces high purity, "exotic" short-lived isotope beams.
- A mosaic of vaporised nuclear reaction products, from interaction between the target and the 1.4 GeV proton beam from CERN's PS booster, diffuses out of the target, into the back of the ion source.
- The element of interest is, in most cases, ionized via resonnance laser ionization. The ionized element is then extracted by the high voltage field applied to the mass separator frontend.
- It is then defelcted by the mass separator magnet, which provides the isotope selectivity. Finally, the resulting beam is analysed by the different ISOLDE experiments.

TWO PHOTON DOPPLER-FREE SPECTROSCOPY

K. Wendt, et al. Hyperfine structure and isotope shift in the 3s2 3p2 3P0,1,2 — 3s2 3p4p 3P0,1,2 transitions in silicon by Doppler-free in-source two-photon resonance-ionization spectroscopy. Phys. Rev. A, 88:052510, Nov 2013.







Let us once again consider the metaphor of the runner in the sea. Now, waves strike him on both side, in opposite directions. If the two sources have the same frequency, the increase in the first side will be compensated by the decrease in the other. As a consequence, it is as if the runner is immobile, thus cancelling the doppler effect.
Once again, this can now be applied for light waves and hot atoms. In principle, if we can retro-reflect a laser beam towards a bunch of atoms, within the region of interaction, the two-photon transition will be independent of the atomic velocity.This technique was demonstrated off-line for Silicon isotopes at the University of Mainz, using an injection-locked Ti:Sa laser, retro-reflected inside the ion source by a mirror placed outside of the chamber. This project aims to apply the same principle on-line at ISOLDE. In this regard, a setup involving the pulsed-Dye amplification of a CW Ti:Sa laser, retro-reflected by a Mo mirror inside the ion source, is currently undergoing tests at the RILIS developpement lab.