Results of Ag Laser Photo-Ionization study for ISOLPHARM Project

Low Energy Seminar
Ph.D. cycle XXXVII

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Introduction

1. Introduction to SPES and ISOLPHARM Project

2. Ionization Techniques

3. Lasers

4. Spectroscopy with Hollow Cathode Lamps

5. Conclusions

ISOL facility at LNL: the SPES Project

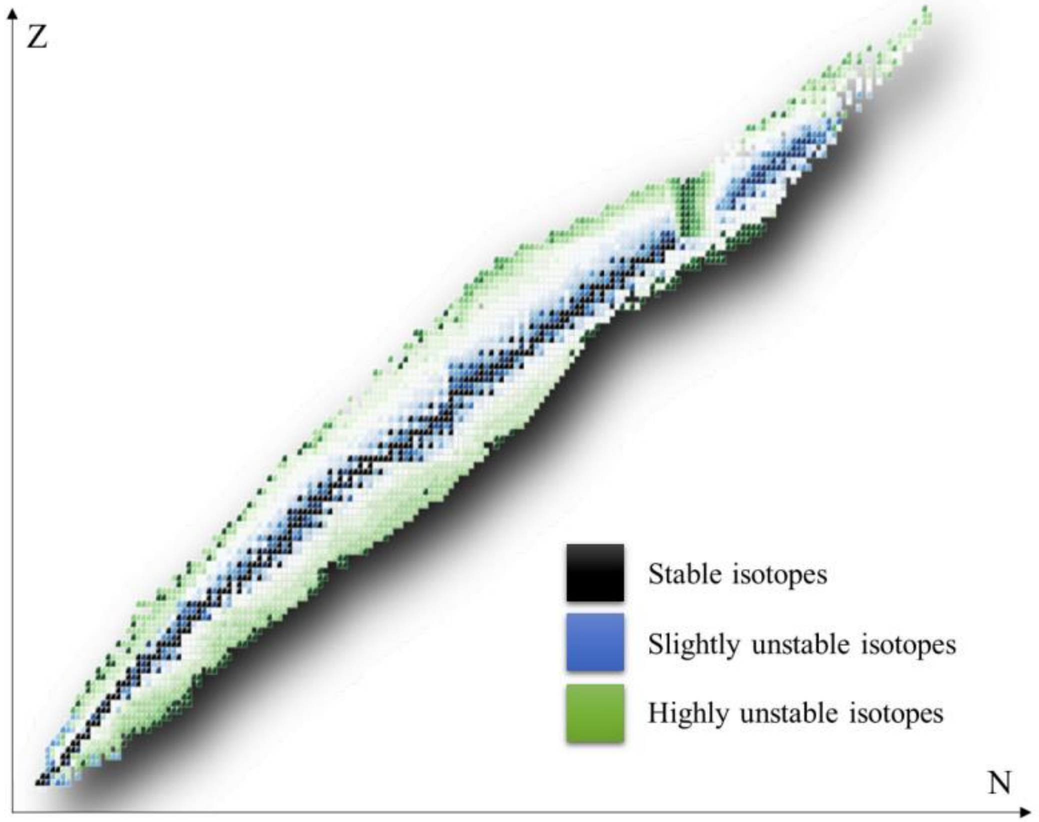
The SPES project (Selective Production of Exotic Species) is devoted to basic research in nuclear physics and astrophysics, as well as to interdisciplinary applications:

There are numerous topics that can be studied by exploring the properties of exotic nuclei:

1. **Nuclear Physics**
   Present physical models of the nuclear structure are based on nuclei very close to the stability valley

2. **Nuclear Astrophysics**
   Better comprehension of the stellar evolution and the elemental abundance in the Universe
   Calculation models fail in reproducing some aspects of the observed abundance pattern

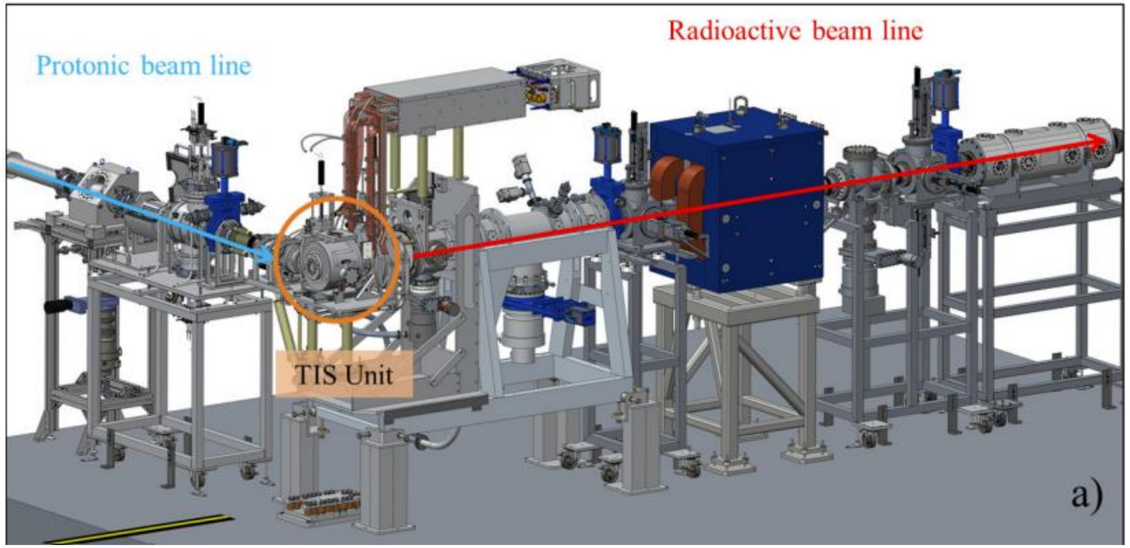
3. **Nuclear Medicine**
   ISOLPHARM project will exploit the radioactive beam produced in the SPES facility to obtain pure isotopic beams without contaminants



ISOLPHARM Project

Radiopharmaceuticals are drugs containing radionuclides and are used in nuclear medicine for diagnosis or therapy of different diseases.

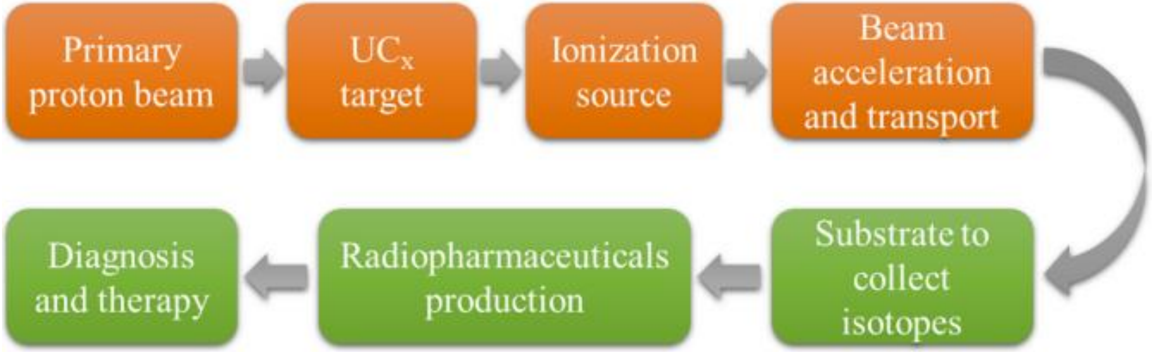
Radionuclides are produced in **cyclotrons or nuclear reactors**:
- High costs for targets
- Low reaction cross-section
- Production of unwanted wastes



ISOLPHARM Project is aiming to use the **Radioactive Ion Beams** (RIBs) facility SPES

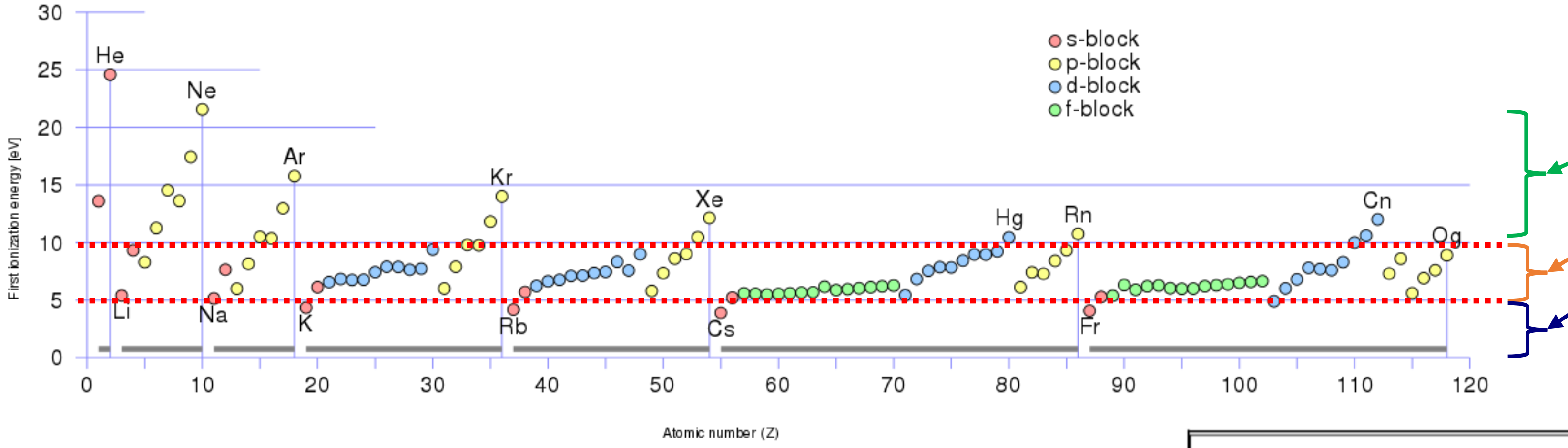
The ISOL Technique could also be used to expand the variety of available medical isotopes

$Ag - 111$ is very promising for cancer therapy:
- β^- emission with half-life 7.45d
- Medium tissue penetration 1.8mm
- Its decay produces low energy γ that can be used for SPECT



Ionization Techniques

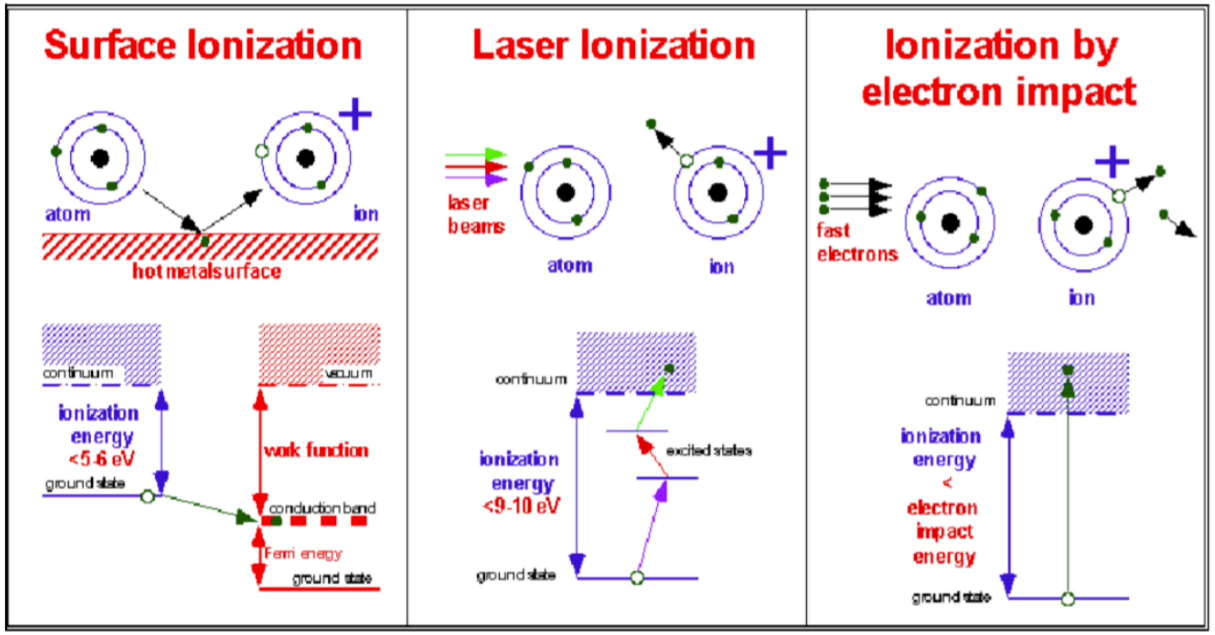
The technique used for ionization depends on the **ionization potential** of a given atom



There are two main ionization procedures:

- **Plasma Ion ionization**
- **Laser ionization**
- **Surface ionization**

Surface Ionization
An atom interacting with a hot surface may lose or gain an atom



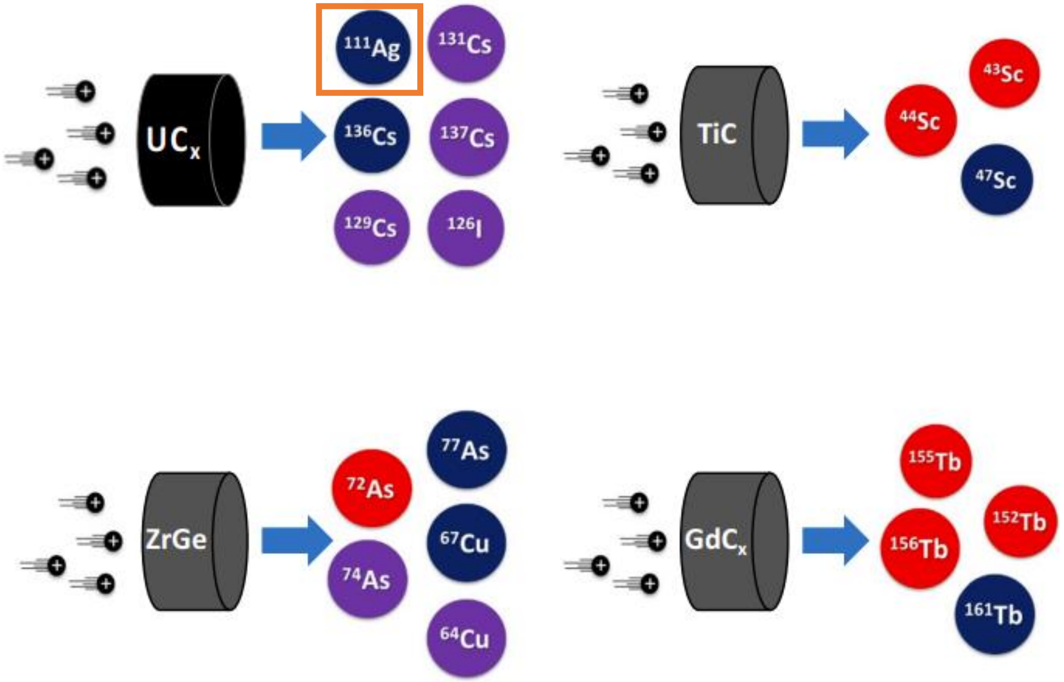
In a hot cavity ions are produced with interactions to the walls
Competition between:

Surface Ionization ↔ Laser Ionization

- High temperature to prevent interaction with walls
- Low temperature to have more neutral atoms

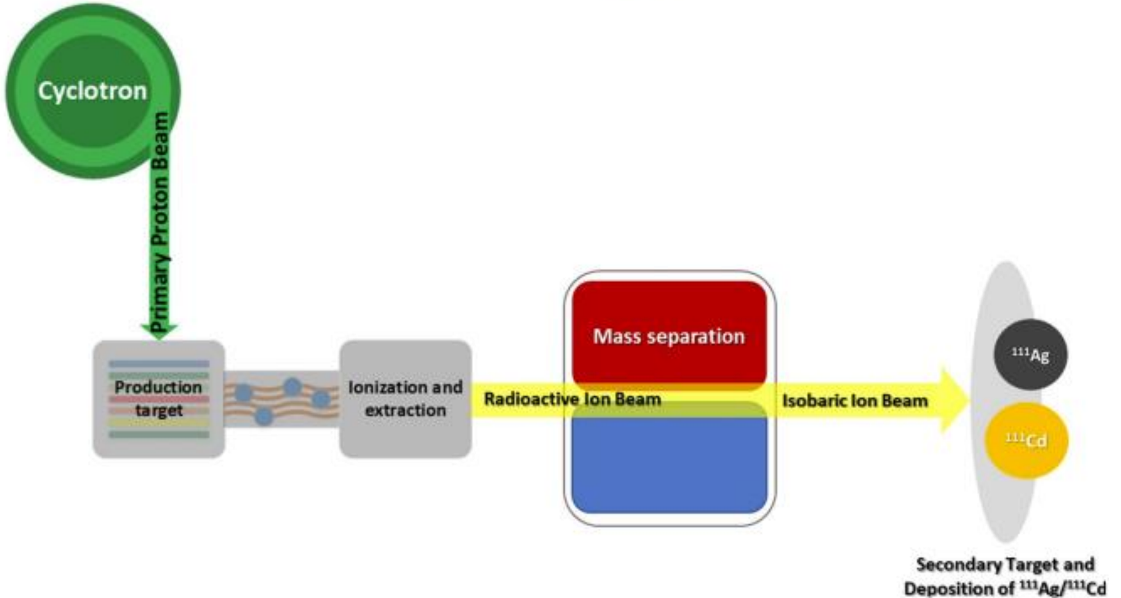
Studies on SPES Working Principle

1. Target interaction with a proton beam ($\sim 40\ \mathrm{MeV}$) accelerated by a cyclotron
2. Neutron-rich radioactive ions will be produced
3. Radioactive nuclei produced in the target will evaporate
4. Mass separation (**isotopes**) performed by an electromagnetic separator
5. An **isobaric** beam is obtained



- Test were performed on **SPES plasma ion source**
- Ionization efficiency of $\sim 15\%$

Resonant Laser Ionization could yield a better result!

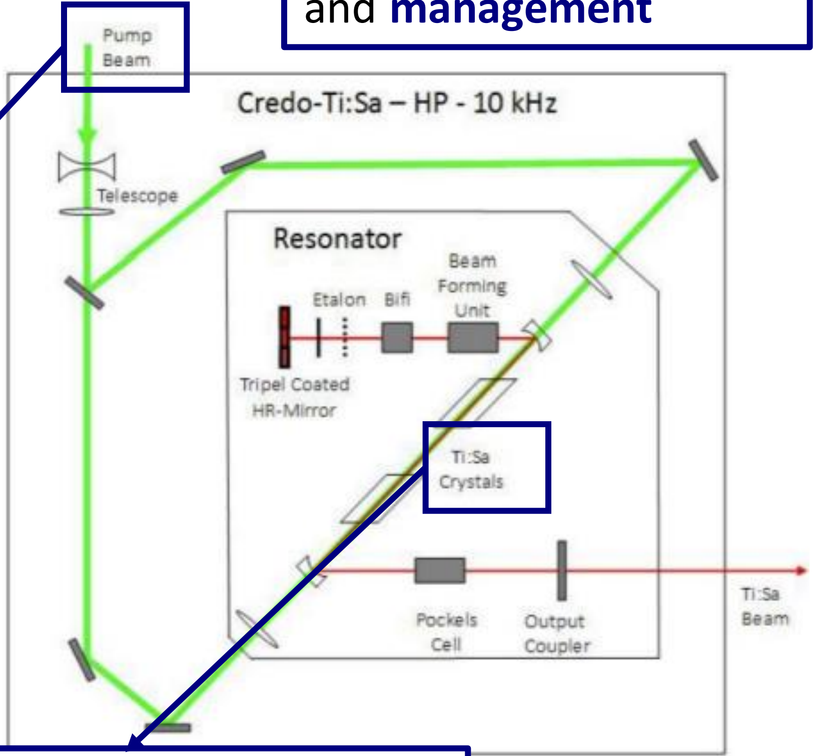


LASER System at SPES

In a Resonant Laser Ion Source (LIS) facility two systems may be used:

1. Dye Lasers
2. **TiSa Lasers**

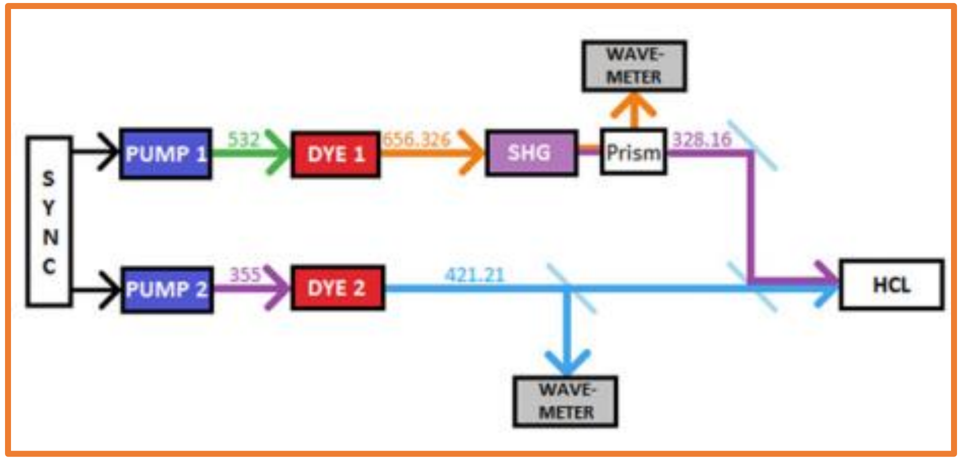
Solid state technology chosen for its **reliability** and **management**



50W emitting
527nm light
50ns pulses
10kHz repetition rate

Parameter	Value
Tuning Range	$690 - 950\,nm$
Pulse Duration (τ_{FWHM})	$30 - 50\,ns$
Repetition Rate	$10\,kHz$
Output Power (λ_{Peak}@$10\,kHz$)	$6,8\,W$
Line-width	$< 6\,GHz$ (One Etalon)
Beam divergence	$< 1,5\,mrad$
Beam size	$1\,mm$ Typ.

Laser apparatus used for Ag studies



Laser	Fundamental			SHG			Power	Pulse length
	λ (nm)	$\Delta\lambda$ (pm)	$\Delta\nu$ (GHz)	λ (nm)	$\Delta\lambda$ (pm)	$\Delta\nu$ (GHz)	(μW)	(ns)
TDL50	656.326	3-3.5	2.1-2.4	328.163	1.1-1.2	3.0-3.3	20-30	20
FL2002	421.402	1-1.1	1.7-1.9	-	-	-	500-550	20

Dye lasers and **Ti:sapphire** are tunable lasers that differ for:

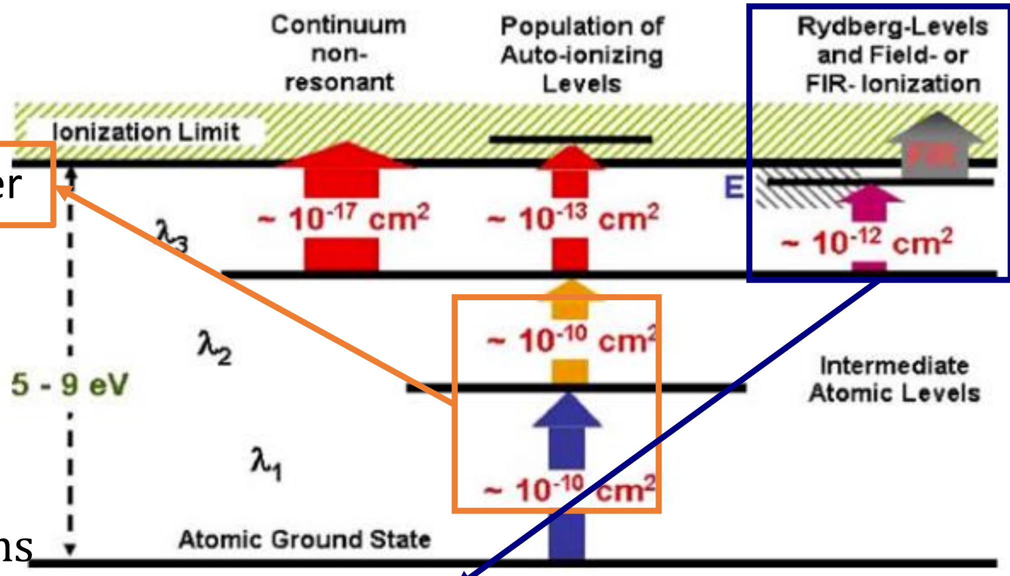
1. Gain medium
2. Wavelength range
3. Pulse Duration
4. Pump Source

Ionization of Silver

The ionization of an atom may happen following three different techniques:

- Continuum non-resonant
- Population of Auto-Ionizing Levels
- Through Rydberg Levels

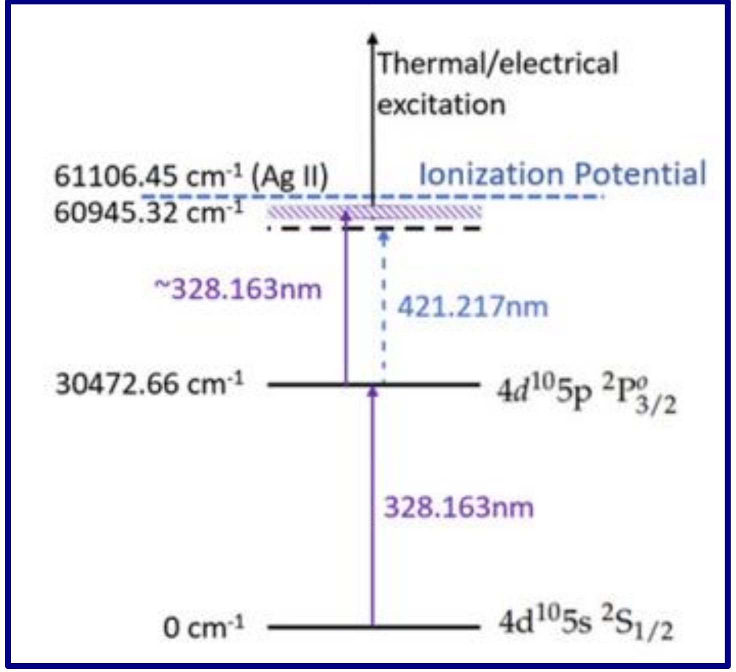
$\sigma_{eff} \sim 100$ times lower



In all cases, **two or three optical steps** in UV ($> 3.5\text{eV}$) or visible ($\sim 2\text{eV}$) are used:

- Excitation along first and second steps can be carried out efficiently
- Lifetimes $O(10)$ ns

To saturate such levels, we need an optical field of intensity: $J \sim 10^{18} \dfrac{\text{photons}}{\text{cm}^2 \cdot \text{s}}$



Rydberg levels present a high main quantum number

- **Long lifetimes** $\geq \mu s$
- Highly susceptible to external input due to long lifetime

Ionization through:
Electric field, Collision and **Thermal excitations**

Line Width and Broadening Effects

If we want to consider a line for our experiment, we need to consider sources of uncertainties when designing our setup:

1. **Uncertainty Principle**
   Short-lived states are associated with a minimum unavoidable uncertainty in energy

$$\Delta E \cdot \tau \geq \frac{\hbar}{2} \rightarrow \Delta \nu \geq \frac{1}{4\pi\tau}$$

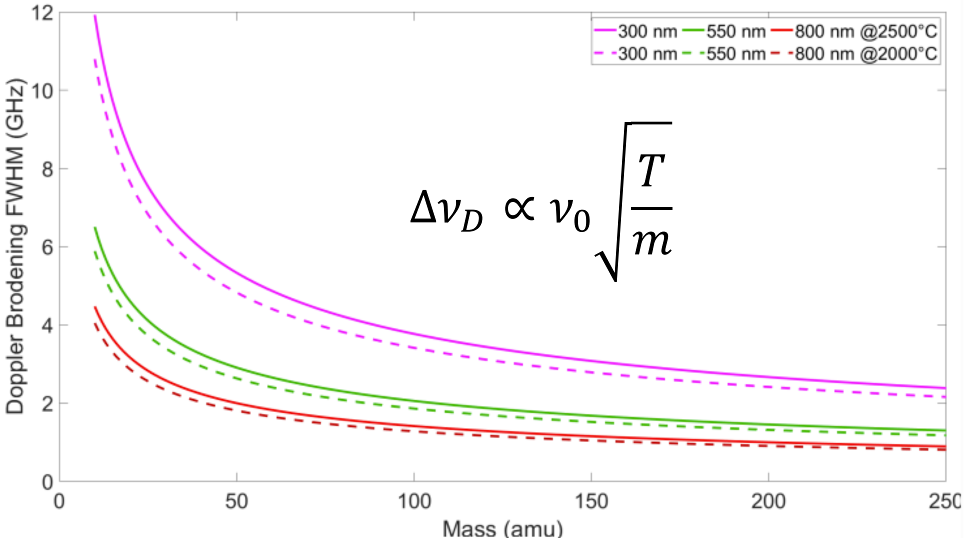
Collisions in gas may shorten the effective state lifetime

2. **Doppler Broadening**
   Effect related to the velocity of atoms with respect to beam longitudinal direction

$$\nu = \nu_0 \left(1 \pm \frac{u_x}{c}\right)$$

Broadening of resonance profile

$$\phi(\nu) = \frac{\exp - \frac{(\nu - \nu_0)^2}{\Delta \nu_D^2}}{\Delta \nu_D \sqrt{\pi}}$$



$$\Delta \nu_D \propto \nu_0 \sqrt{\frac{T}{m}}$$

3. **Power Broadening**
   Effect related to the power of the laser with respect to the saturation intensity of the transition

Gaussian profile + **Lorentzian profile** → **Convolution** → **Voigt profile**

$$FWHM_V \sim 0.5346 f_L + \sqrt{0.2166 f_L^2 + f_G^2}$$

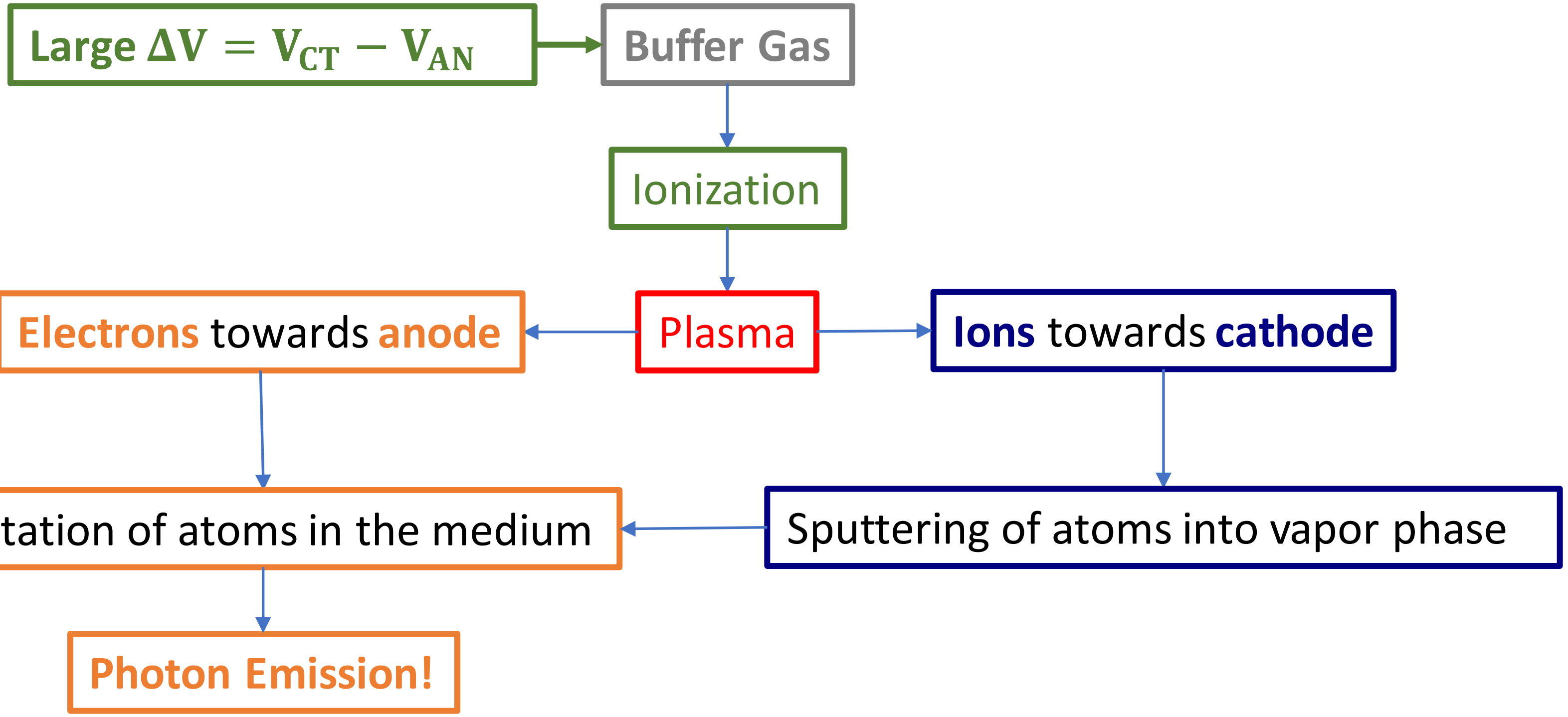
- **Core**: Mainly gaussian
- **Tails**: Lorentzian

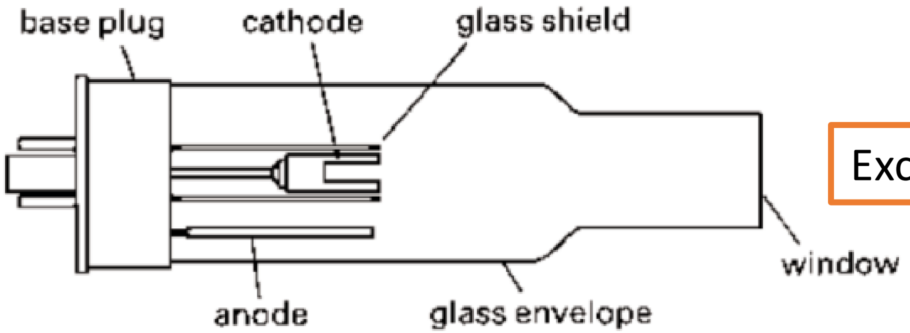
Hollow Cathode Lamps

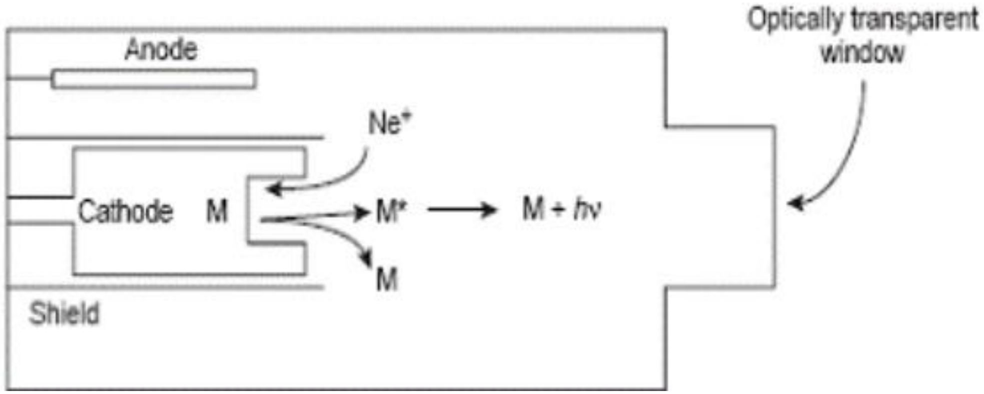
Hollow Cathode Lamps are designed to provide spectral emission of different elements with a high spectral purity

Structure

- Glass Tube
- Cathode
- Anode: Element under study
- Buffer Gas: Noble Elements (e.g. **Argon**)







Bandwidth resolution depends on many phenomena, in particular:

1. **Doppler Broadening**

2. **Self-Absorption**
A photon is absorbed by another atom before escaping

Testing Ag Ionization Scheme with Hollow Cathode Lamps

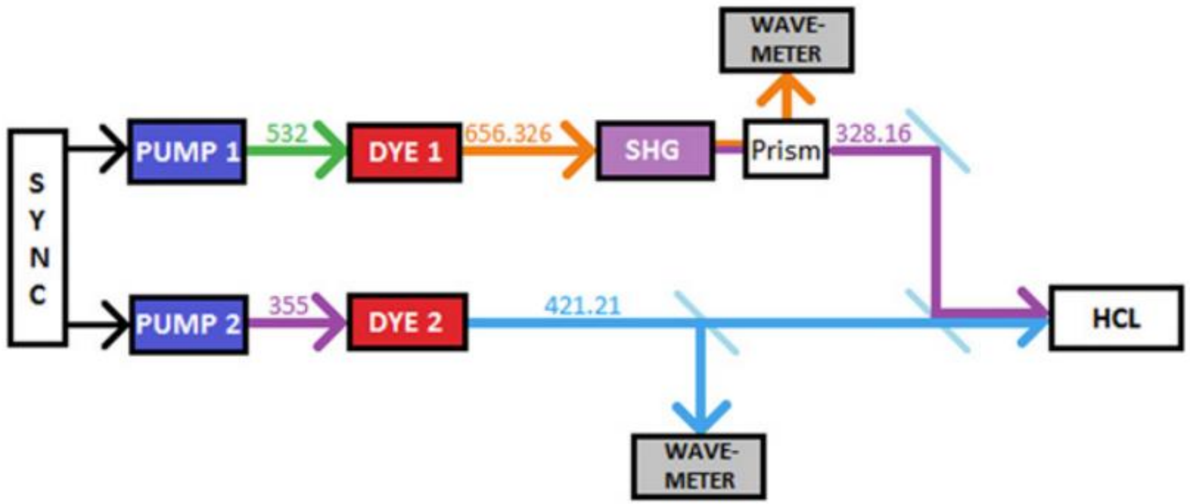
The emission can be studied exploiting the **Opto-Galvanic Effect**

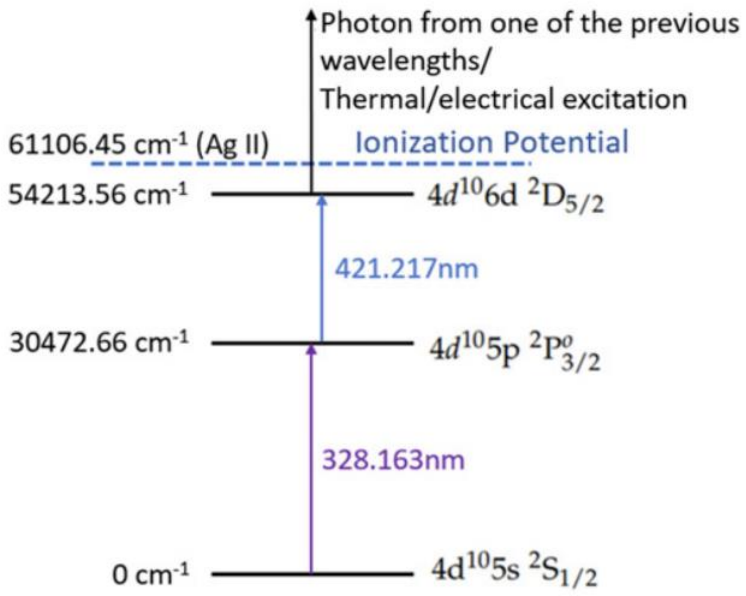
Laser illumination of a discharge varies the balance of atomic level populations in gas. This effect will translate in different electric properties of the gas.

Depending on the ionization rates of the level favored by the laser, there could be an increase or decrease in the readout current

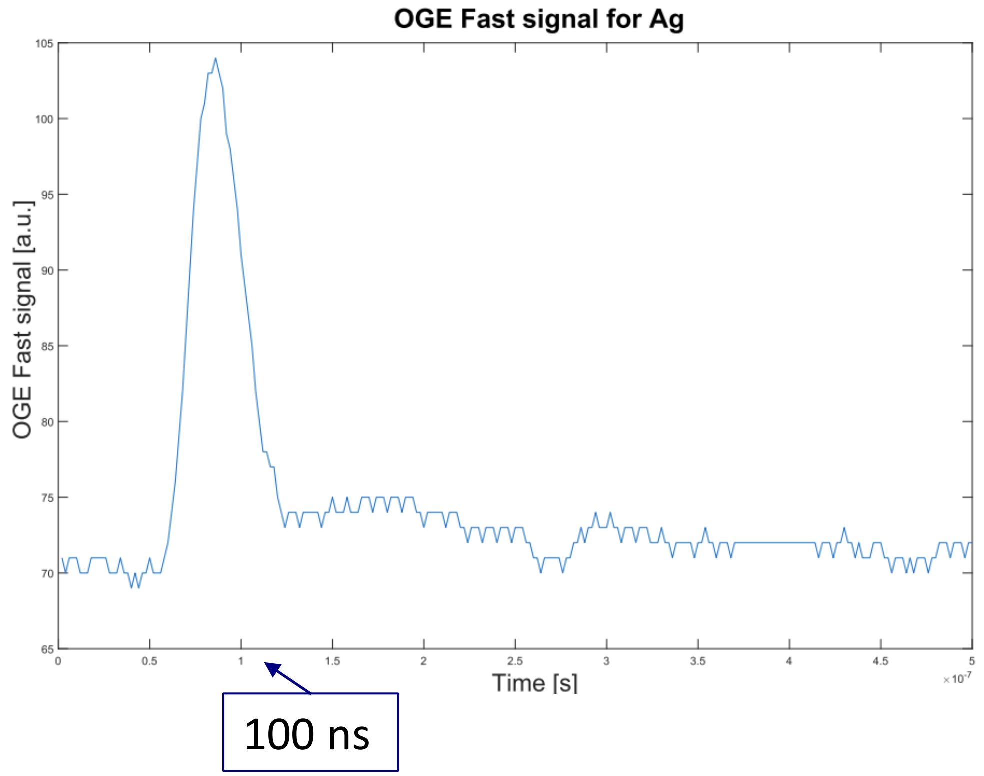
OGE signals can be considered **proportional** to the **intensity of resonant radiation**

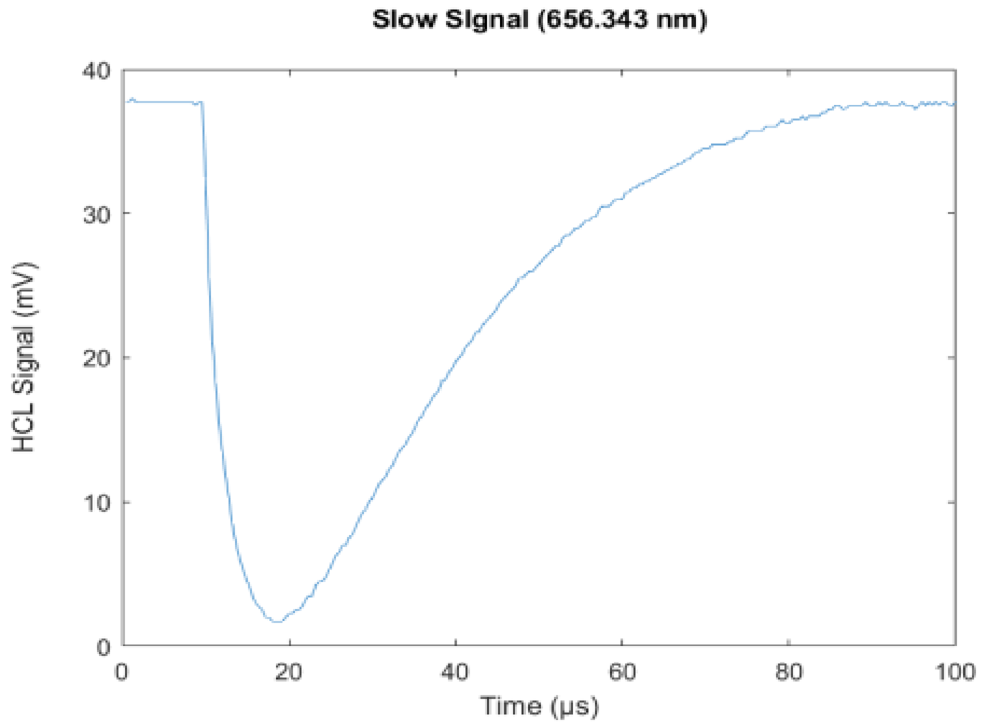
A study on OGE signals has been setup to probe Ag ionization scheme:





OGE Signals





- **Fast OGE**

  Laser pulse creates a direct ionization in the discharge

  Time duration: Similar to Laser Pulse $O(ns)$

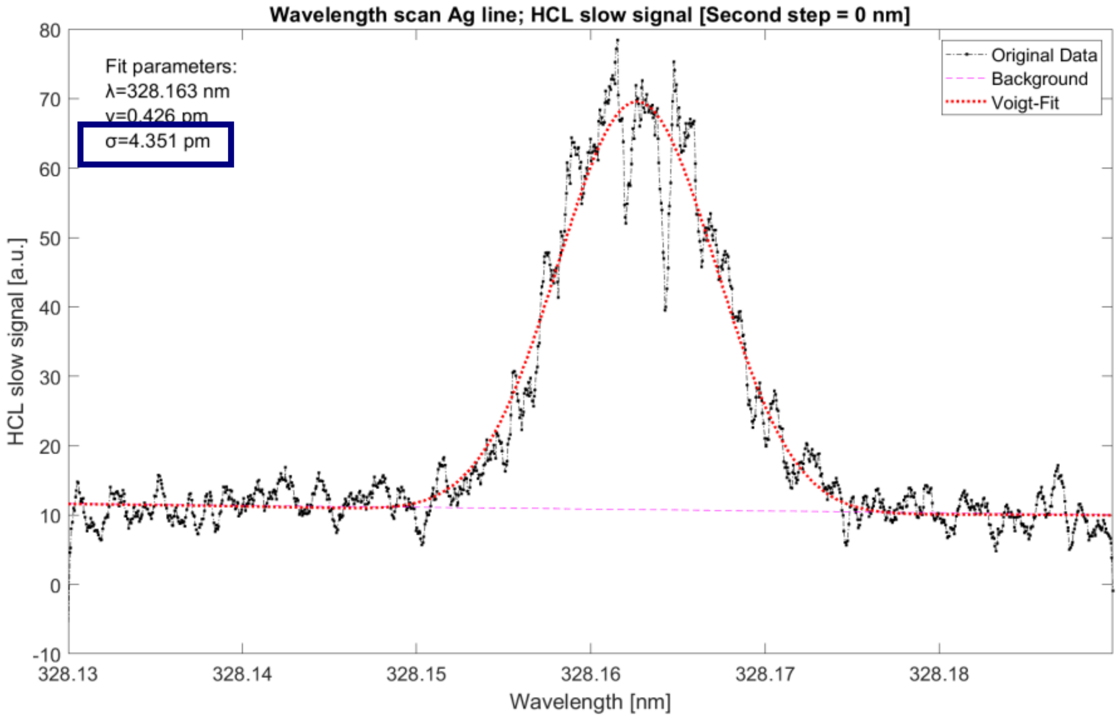
- **Slow OGE**

  Laser pulse modifies atomic state populations and therefore the gas electric impedance

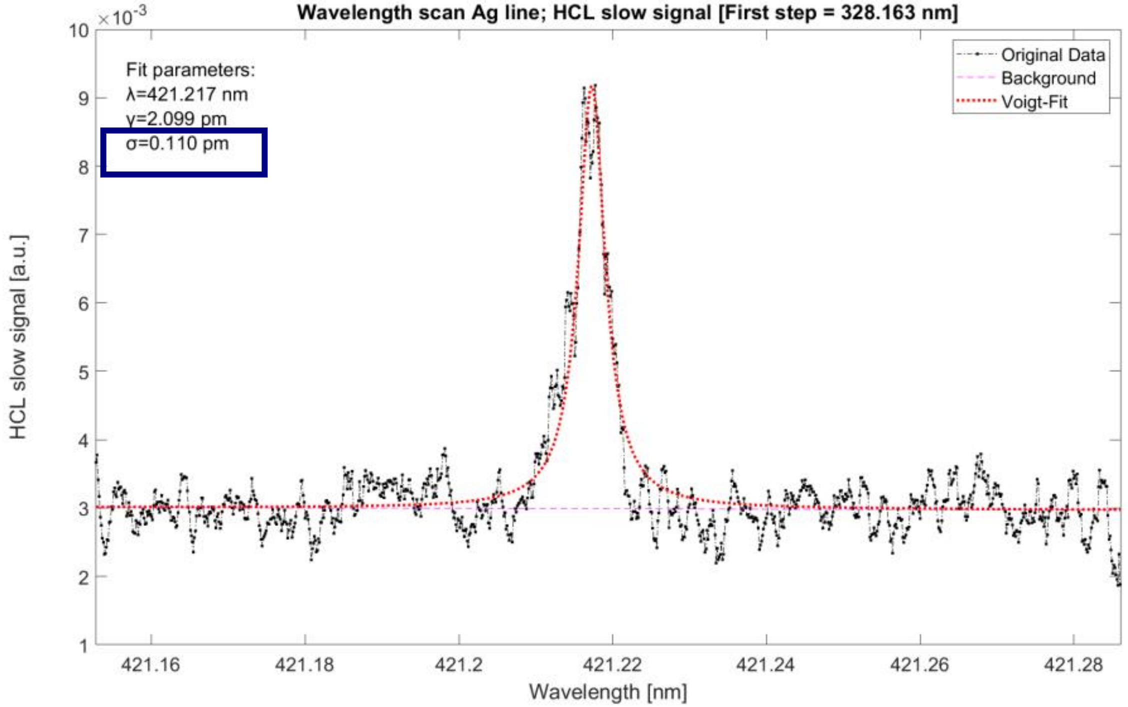
  Time duration: $O(\mu s)$

Slow OGE Signal

1. A scan on OGE signal amplitudes is performed only using the first laser



2. Keeping the best fit for first step as reference, a scan is performed for the second line



The difference in width of Voigt fit is noticeable
The broadening of first peak cannot be explain by only Doppler broadening

Reminder:
$\Delta\nu_D \propto \nu_0$

Fast OGE Signal

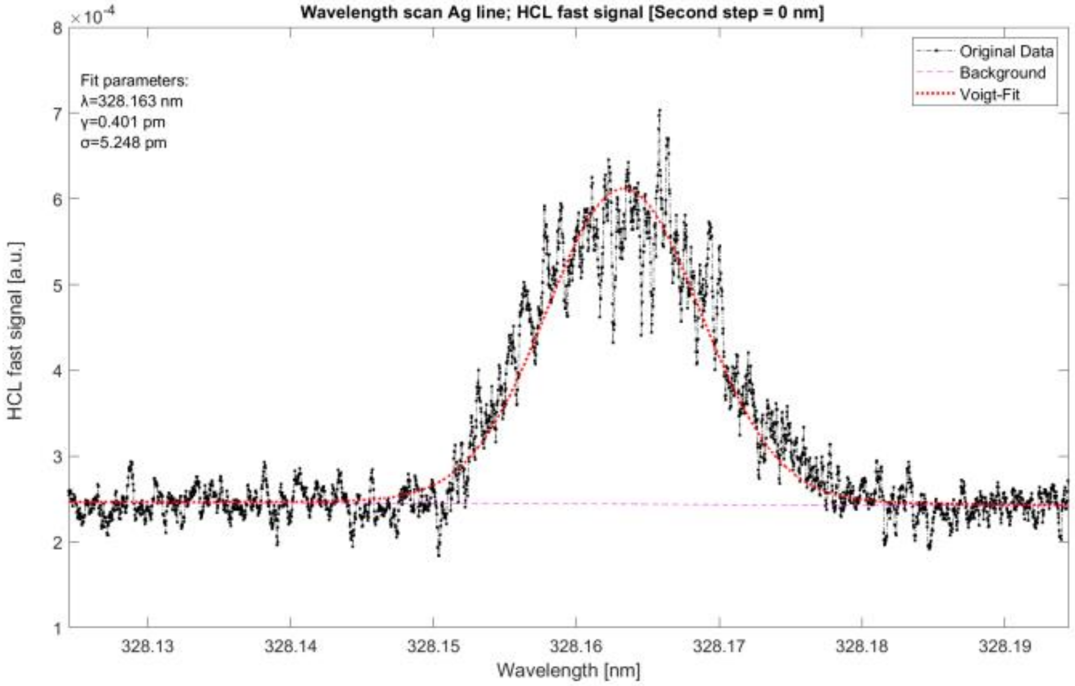
The study of fast OGE signals is useful for understanding high-lying Rydberg levels near Ionization Potential

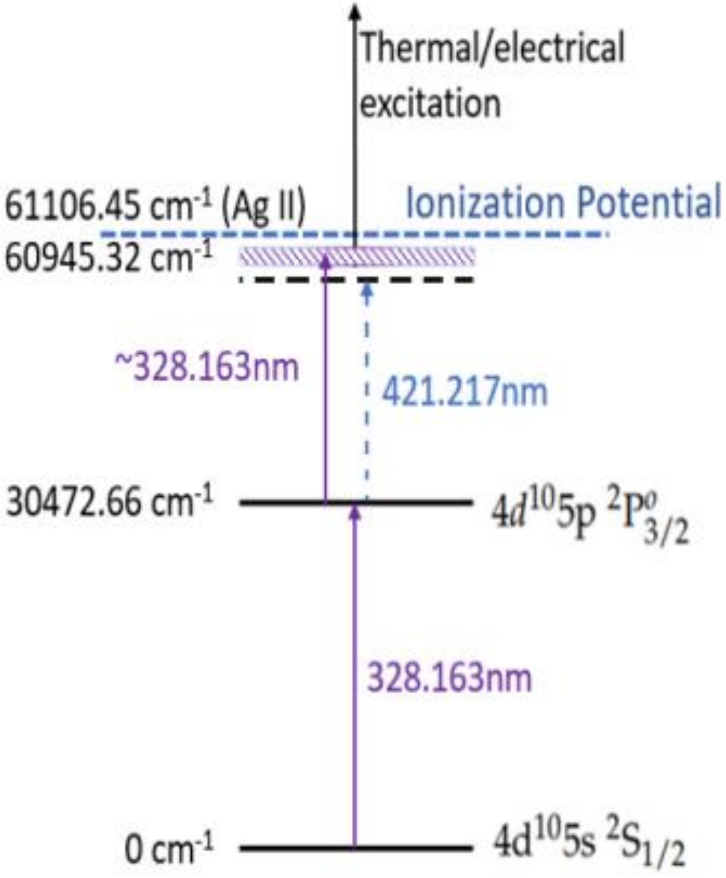
In Ag-HCL, a large amount of Ag atoms are in the excited state associated to $\lambda \sim 328.163 \text{ nm}$

Fast signals might be created by:

- Double absorption of photons at $\lambda \sim 328.163 \text{ nm}$
- Resonance transitions to energy levels $\lambda \sim 2 \times 328.163 \text{ nm}$

  Ionization is achieved thanks to interactions with Electric Field in the HCL





The distinction of Rydberg states requires a laser with a finer bandwidth

Conclusions

SPES facility can be used to improve the production of important radionuclides employed in many Medicine applications

Ag is under study due to its $\beta -$ emission

To create ions that can be accelerated in ISOL facility, there are three different techniques:

- Surface ionization
- Plasma-ion ionization
- Laser ionization

A way to probe Ag ionization scheme has been developed and tested in an offline setup, using:

- Time of Flight Mass Spectrometer
- Hollow Cathode Lamp

The results are encouraging for the development of ISOLPHARM Project!

Thanks for your attention!

LASER

How does a LASER work? → Light Amplification by Stimulated Emission of Radiation

We need:

- **Optical Cavity** to obtain a stationary wave
- **Optical Amplification**

Photons emitted in the **"stimulated emission"** have the **same Energy and phase of the initial photon**

↓

Amplification of Radiation Amplitude!

At equilibrium:

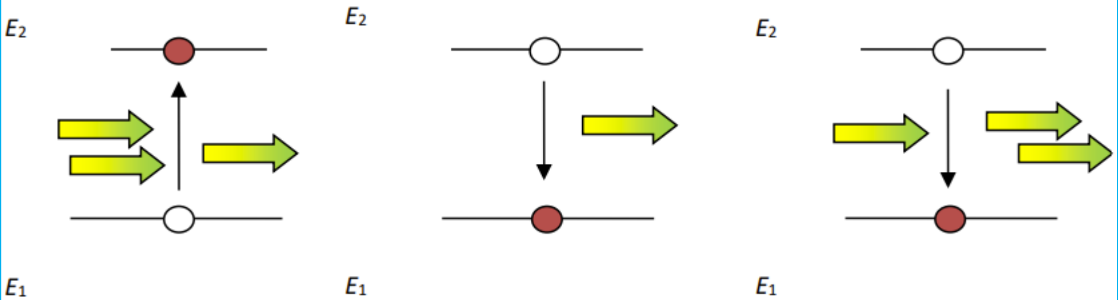
$$\frac{\left(\frac{dN_2}{dt}\right)_{st}}{\left(\frac{dN_2}{dt}\right)_{sp}} = \frac{1}{\exp\frac{h\nu}{kT} - 1}$$

If we want a net gain:

$$\left(\frac{dN_2}{dt}\right)_{st} \geq \left(\frac{dN_2}{dt}\right)_{sp}$$

We need to set the system in a *meta-stable* configuration with a large number of excited atoms: **Population Inversion**

Equilibrium of atoms in an optical field



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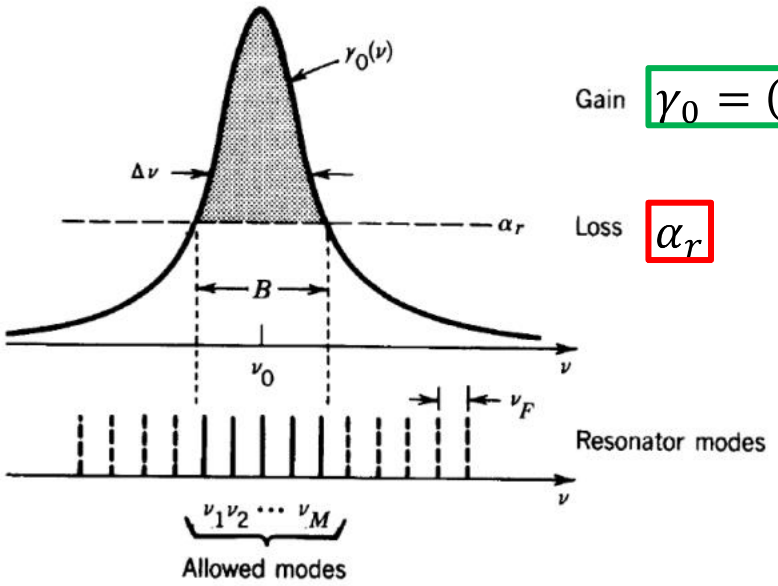
"Pendulum Analogy"



Gain $\gamma_0 = (N_2 - N_1)\sigma$

Loss α_r

Solid-State Lasers and Dye Lasers

The optical medium for this dye lasers are **dye molecules solved in liquids**

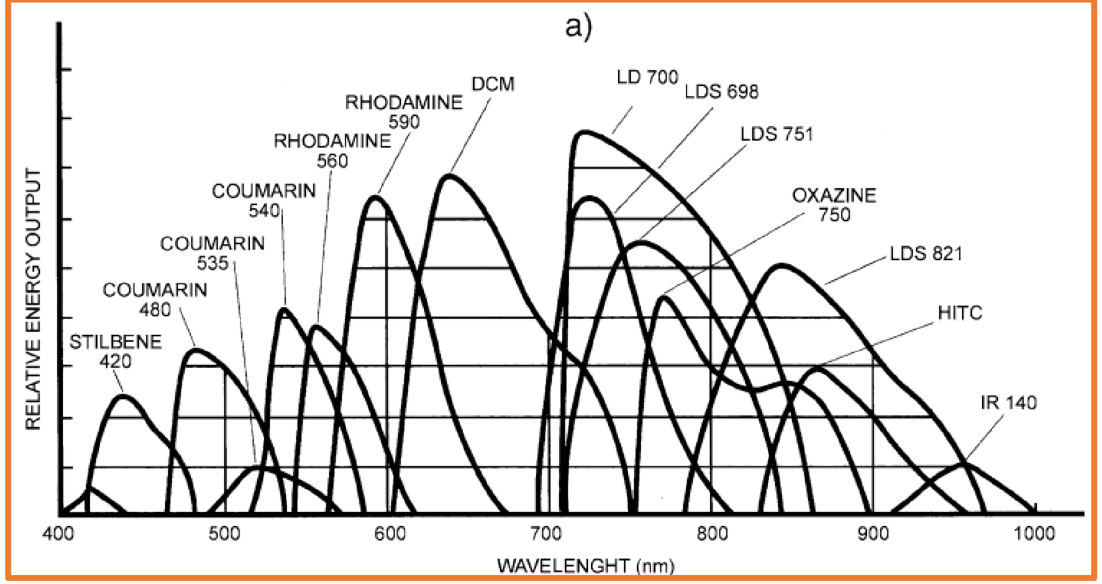
Range
$300\text{ nm} - 1200\text{ nm}$

Extended Range
$100\text{ nm} - 4000\text{ nm}$

In solid state lasers, Absorption and Emission spectra of **crystalline and amorphous solids** can be modified by doping with ions

Range
$650\text{ nm} - 2500\text{ nm}$

Ti:sapphire $Al_2O_3{:}\,Ti^{3+}$
$670\text{ nm} - 1100\text{ nm}$



Dye lasers and **Ti:sapphire** are tunable lasers that differ for:

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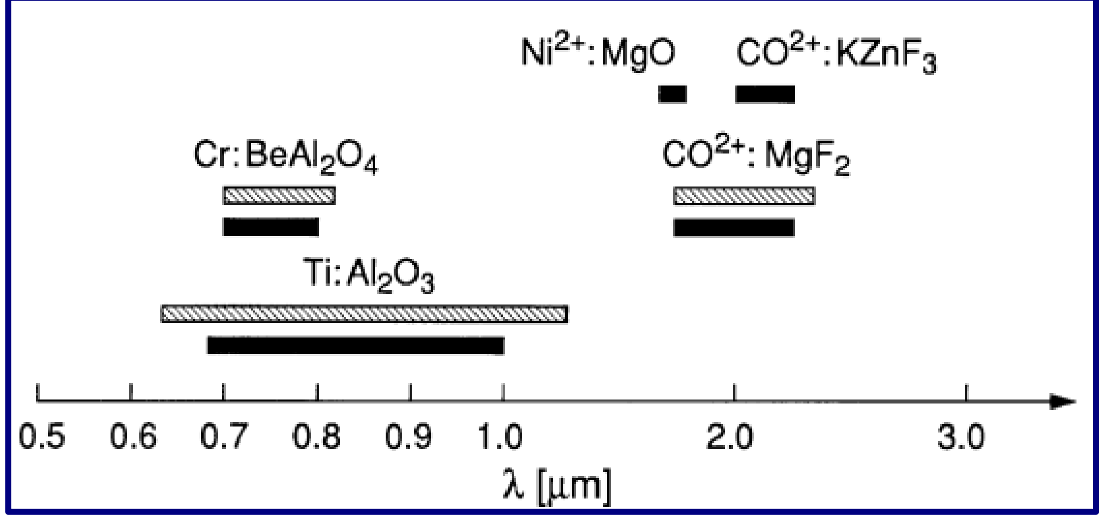

in ranges $\lambda > 700\text{nm}$ **Ti:sapphire** has superior characteristics due to:

- **Higher output power**
- **Better frequency stability**
- **Smaller linewidth**
- **Reliability**

(But cost is larger)