Chapter 3

TRI\(\mu\)P Facility

In the periodic table of elements shown in Fig. 3.1 we find that most of the laser cooled and trapped species belong to the one valence electron (alkali) and two valence electron (alkaline earth) systems. Also noble gas atoms were trapped exploiting their metastable states. In addition, there are a few other species scattered over the periodic table that were trapped. The scientific goal of the cold atom research spans, to name a few, from precision spectroscopy to quantum fluids and from many-body physics to collision studies. Our interest is in the heavy alkaline earth elements barium and radium. Barium, which has stable isotopes, has an atomic level scheme similar to radium. It is available in metallic form that can be readily used for the experiments. Radium, a radioactive element has to be extracted from radioactive sources or produced by nuclear reactions for experiments at facilities like TRI\(\mu\)P at KVI. The rare and short lived radium isotopes offer unique possibilities for investigating fundamental symmetries in physics complementary to high energy physics experiments.

World wide various experimental efforts are in progress using radioactive isotopes in high precision experiments to test the limits for the validity of the standard model. To provide short lived isotopes at KVI, Groningen, the TRI\(\mu\)P (Trapped Radioactive Isotopes: \(\mu\)icro laboratories for fundamental Physics) facility has been set up in the last 4 years [76]. The facility produces radioactive nuclides and provides them, after slowing down, as low energy ion beams to experimental areas. The facility is open to outside users and first experiments have been made. We will describe briefly the complete facility consisting of a production target, a magnetic separator, thermal ionizer, radio frequency quadrupole cooler and buncher, low energy beam line, and laser facility for neutral atom traps. The different components of the TRI\(\mu\)P facility are schematically shown
Figure 3.1: Periodic table of elements. Elements marked with arrows and square blocks are the neutral atoms that have been laser cooled and trapped. They have favorable level structures which allow cooling and trapping with a single laser from the ground state or a metastable excited state. The proposed heavy alkaline earth elements barium and radium are also shown. They require a number of additional lasers for repumping the atoms into states with suited transitions for cooling and trapping.

Our group is interested to use the facility to perform experiments probing fundamental symmetries as described in Chapter 2. In particular we are interested in nuclear $\beta$-decay for T-violation studies and for CP-violation by searching for a permanent electric dipole moment with radium.

### 3.1 Isotope Production and Separation

#### 3.1.1 AGOR

The superconducting cyclotron AGOR (Accélérateur Groningen Orsay), at KVI, accelerates both the light and heavy ions. For heavy ions the charge-to-mass ratio, $Q/A$, determines the achievable maximum energy. In Fig. 3.3 the available beams are shown. The maximum energy for protons is 190 MeV. Different sources are
3.1. Isotope Production and Separation

Figure 3.2: Conceptual view of the TRIμP facility consisting of a production target to produce radioactive isotopes by nuclear reactions with beams from the AGOR cyclotron. A magnetic separator is used for the selection of isotopes of interest. The thermal ionizer and the RFQ cooler and buncher stages are for slowing the high energy isotopes. Atom traps are for storing and for conducting high precision experiments with the goal to search for physics beyond the Standard Model [17].

available to produce a wide range of primary beams. To accelerate heavy ions like lead (Pb) the vacuum needed to be improved to be better than $10^{-7}$ mbar in the accelerator. Overall the AGOR cyclotron is upgraded to provide beams for the TRIμP facility. The goal is 1 kW of beam for any accelerable ion. So far 100 W has been reached, which makes AGOR, a state-of-the-art cyclotron with high beam current for heavy ions.

Production Target

A hydrogen gas target cooled to liquid nitrogen temperature is in use that is compatible with the typical beams and inverse reaction dynamics for which the separator is designed. The use of a gas target has important benefits over solid targets. The polyethylene targets used during the commissioning phase of the magnetic separator showed rapidly diminishing hydrogen content at a few tens of nA beam current. The target was built by a collaborating group at North Carolina University, USA [77].
3.1.2 The Magnetic Separator

The different types of nuclear reactions that will be used required the design of a dual-mode combined fragment and recoil magnetic separator [17]. The separator was designed at KVI. The layout of the magnetic separator is shown in Fig. 3.4. It consists of two pairs of dipole magnets for the particle momentum selection, four pairs of quadrupoles for focussing and components such as beams stops, beam profile detection and slits. Two target positions, $T_1$ and $T_2$, are foreseen for the different kinematics of the various production methods. It was built in 2003 and commissioned in May 2004. The magnetic separator can be operated in two modes. One is the fragmentation mode and the other is the gas-filled mode. In the fragment-separator mode, target $T_1$ is used. In the gas-filled mode of operation, for fusion-evaporation reactions gas filling of the second part is used to efficiently...
3.1. Isotope Production and Separation

Figure 3.4: Layout of the TRIμP dual-mode magnetic separator. The separator can be used in fragment-separator (target position T1) and in gas-filled (target position T2) mode. B1-B4 are the dipole magnets for particle momentum selection and Q1-Q9 are the quadrupole magnets for focussing. SH1-6 are the slit systems and a hexapole Hex.

collect heavy ion products which are spread out over many atomic charge states. For this the target station T2 is used.

The TRIμP separator is made available for various physics experiments by the user community in collaboration with our group. They include production of $^{19}$Ne to measure the half-life for the $^{19}$Ne to $^{19}$F decay in collaboration with the North Carolina State University group [78]. An experiment to study particle unstable states in $^{12}$C populated in the $\beta$-decays of $^{12}$N and $^{12}$B was carried out. This experiment is led by the Aarhus university group [79]. The details of the magnetic separator such as design, construction and commissioning can be found in the thesis of Emil Traykov [80].

Fragment-separator mode

The fragmentation mode was tested with the $^1$H($^{21}$Ne, $^{21}$Na)n reaction in inverse kinematics. Initially, the basic ion-optical parameters are tested using the 43 MeV/nucleon $^{21}$Ne$^{7+}$ beam ($B\rho = 2.8$ Tm). After successful commissioning
The time-of-flight (TOF) spectrum (relative to $^{20}$Ne shown at the focal plane of the magnetic separator consists of only $^{21}$Na and a small contamination of stable $^{20}$Ne, which could be reduced to below 0.5%. Here $^{21,20}$Na isotopes have the same magnetic rigidity ($B\rho$) but different velocities. Hence $^{21}$Na arrives at the detector earlier than $^{20}$Ne.

and verification of ion optics and design parameters, the first radioactive $^{21}$Na isotope was produced using the (p, n) reaction in inverse kinematics with this $^{21}$Ne beam. A silicon detector of 20 mm diameter and thickness of 150 $\mu$m placed in the focal plane of the magnetic separator was used to measure the yield of $^{21}$Na. The spectrum shown in Fig. 3.5 is the time-of-flight spectrum of particles arriving at the detector. The typical $^{21}$Na production rates during the commissioning were $8 \times 10^4$ particles per second. The $^{21}$Na isotope beam was used for first physics experiments to measure the $\beta$-decay branching ratio in $^{21}$Na to the excited state of $^{21}$Ne at 350.5 keV [81]. The population of this state is of significance for $\beta - \nu$ correlation experiments of $^{21}$Na planned by our group.

Gas-filled Separator Mode

The separator has been tested in gas-filled mode. In this mode the first part of the separator acts as a beam line and the second part as a recoil separator. The vacuum (first part) and gas-filled sections (second part) are separated by a thin Havar foil of 2.5 $\mu$m. This mode is required for the production of radioactive radium isotopes for the EDM experiment. For example, $^{213}$Ra can be produced by the fusion-evaporation reaction in inverse kinematics. In these reactions the products
3.1. Isotope Production and Separation

Figure 3.6: Experimental charge-state distribution of a $^{206}$Pb beam in the focal plane of the TRIP separator setup. The full circles represent the charge state distribution of $^{206}$Pb beam without gas filling of the second part of the separator after passing the Havar foil and the carbon target. The full triangles represent the all charge states of $^{206}$Pb beam concentrated in a single peak with the gas filling of the second part of the separator.

are not fully stripped. They leave the target with charge states that are widely distributed. The gas in the second part of the separator causes reaction products to loose and gain electrons rapidly. As a result they move along a trajectory with an effective average charge. It also provides additional differential stopping to separate primary beam and the recoil products further.

To test the separator in gas-filled mode a $^{206}$Pb$^{29+}$ beam of 8.4 MeV/nucleon is passed through a Havar window of 2.5 μm thickness before impinging on a 4.2 mg/cm$^2$ thick $^{12}$C target. $^{206}$Pb instead of the more abundant $^{208}$Pb was used because the $^{206}$Pb($^{12}$C, 5n) $^{213}$Ra has the maximal cross-section. By passing through the Havar foil the lead beam is stripped to a distribution of charge states centered near 60$^+$. The inverse kinematics allows $^{213}$Ra recoils to get out of the carbon target. The results of the testing of the separator in gas-filled mode are shown in Fig. 3.6. The charge distribution of the lead beam after passing the Havar foil and the carbon target without gas filling is given by the full circles. A total of eleven charge states were observed with a maximum intensity at $q = 60$. A Gaussian distribution fit with a full width at half maximum (FWHM) of 9%
\( \delta p/p \) is shown as a line through the points. A more detailed measurement over two charge states indicated by the two dashed Gaussian curves, show a FWHM of 0.37\% \( \delta p/p \) for individual charge states. The triangles represent a scan after filling the second part of the separator after the Havar foil with 2.5 mbar Argon gas. The eleven separated charge states are now concentrated in a single peak corresponding to an average charge state due to the statistical process of charge-state changes in the gas. It can be observed from the fitted dotted curve that the resulting distribution is well reproduced by a Gaussian distribution with a FWHM of 1.4\% \( \delta p/p \).

### 3.2 Low Energy Beam Preparation

In order to perform the precision measurements, radioactive ions produced need to be cooled and trapped in atom traps. The cooling procedure needs to be fast and efficient in view of the short lifetime of the isotopes. This is done with the thermal ionizer and the radio frequency quadrupole cooler and buncher.

#### 3.2.1 Thermal Ionizer

The thermal ionizer shown in Fig. 3.7 is used as a first stage of cooling to stop and re-ionize fast radioactive nuclides produced and separated with the TRI\( \mu \)P separator. The main principle of the thermal ionizer is to stop the high-energy ions in a solid. It is ideal for alkali and alkaline earth elements that have low ionization potential [82]. The thermal ionizer consists of a stack of 10 tungsten foils each 1\( \mu \)m thick and separated by 1 mm to stop the reaction products. The catcher is placed in a tungsten cavity of diameter 30 mm and length 25 mm. The cylinder wall with a thickness of 0.1 mm is heated by electron bombardment and radiation from a tungsten filament surrounding it.

The reaction products pass a few thin tungsten foils, serving as heat shields and energy degraders. After stopping, the reaction products will diffuse out of the foil at these high temperatures. The time scale depends on the diffusion constant, which is highly sensitive to the temperature [82]. Collisions with the surface of the foil and the cavity body ionize these atoms with a high probability. The reaction products can now be extracted as ions with a suitable electric field. The difference between the ionization potential of the reaction product and the foil material determines the ionization probability and the re-neutralization after each collision with the surface. The thermal ionizer was tested successfully in December 2005 using the reaction \( ^1 \text{H}(^{20}\text{Ne}, ^{20}\text{Na})n \) at 22.7 MeV/nucleon [83]. Up to
now at least 2.5% of the primary beam of $^{20}$Na ions was extracted at a cavity temperature of at most $2100^\circ$ C. Improvements of the thermal ionizer are under way. First experiments with $^{21}$Na isotope are planned.

### 3.2.2 Radio Frequency Cooler and Buncher

A segmented radio frequency quadrupole cooler and buncher is the second stage of the cooling procedure in the TRI$\mu$P facility, which is shown in Fig. 3.8. Input ions coming from the thermal ionizer have an energy spread of several eV. The RFQ cooler and buncher consists of two identical segmented RFQ units of 330 mm length, separated by a small aperture for the purpose of differential pumping. The quadrupole rods are 10 mm apart and segmented to apply an axial field gradient. The segments are connected by a dc resistor chain which allow for
Figure 3.8: 3D-drawing of the segmented RFQ cooler, the RFQ buncher and the pulsed drift tube placed in standard NW160 vacuum chambers. Isotope beam from the thermal ionizer is further slowed down in energy with the RFQ1 having buffer gas. RFQ2 is to trap the ions and extract them in pulsed mode with a drift tube. The singly charged ions will be transported to the neutral atoms traps (MOT).

a dc potential along the axis, while the radio frequency is capacitively coupled to the segmented electrodes [84, 85].

The RFQ system was commissioned using $^{23}$Na$^+$ ions with energies of 10-30 eV. In the first RFQ ions are slowed and transversely cooled by collisions with helium buffer gas at a pressure of about $3 \times 10^{-2}$ mbar. A small drag potential of about 0.5 V/cm moves the ions along the axis. The second RFQ operates at a pressure ten times lower than the first one. The fine segmentation along the axis provides the possibility of confinement in all three dimensions. This is used to accumulate ions and then extract them in a pulse. The axial potential is shaped to allow for the trapping of ions near to the exit. The potential depth is on the order of 5 V. The ions can be ejected into a pulsed drift tube accelerator by switching the last electrode by several 10 V. Preliminary measurements indicate that more than 30% of the ions entering the device are transferred into the drift tube. The drift tube is pulsed and the ion pulse is detected by a micro channel plate (MCP) in the low energy beam line. Measuring the transmission of the ions and optimizing the settings are the main issues of the commissioning. Simulations, commissioning measurements of the radio frequency cooler and buncher and other technical details are described in the thesis of Emil Traykov [80].

The ion pulses from the drift tube are transported in an electrostatic low energy beam line, consisting of electrostatic elements for steering and focussing of
3.3 Laser Facility at TRIμP

High precision experiments will be carried out using modern atomic physics techniques like laser cooling and trapping of atoms. In the case of alkali atoms like sodium laser cooling and trapping techniques are well established and KVI has expertise. But, for our other experimental work we need to develop the laser cooling and trapping techniques. They have not been attempted for laser cooling or trapping till date to the best of our knowledge. One of the tasks within the TRIμP project as a facility is the establishment of the infrastructure for the atomic laser spectroscopy. Prior to that there was no laser spectroscopy laboratory available at KVI. We started with the development of grating stabilized diode lasers, built our experimental setups and developed spectroscopic techniques. The laser developments were needed to provide light at different wavelengths. For the lasers, control electronics like temperature controllers and high voltage amplifiers were developed. In addition to the above signal control electronics for the frequency stabilization and modulation of the lasers and the optical detectors for sensitive low-level light detection were designed and developed.
3.3.1 Diode Lasers

Semiconductor diode lasers with single and stable output frequency are in use for high-resolution spectroscopy and laser cooling and trapping of atoms because of their wavelength selection and compactness [88, 89]. A review on the properties of semiconductor diode lasers and their usage in atomic physics experiments can be found elsewhere [90]. We use grating stabilized diode laser systems, which were built in our laboratory for barium spectroscopy. We describe the layout in this section.

Laser diodes are extremely sensitive to optical feedback. Making use of this sensitivity, light is coupled back into the laser diode from a grating as wavelength selective element. The frequency tuning of the diode laser can be achieved by three parameters: the temperature of the laser diode, the injection current of the diode and the tilting angle of the grating. The tuning range for each of the parameters is typically a few GHz. The combination of grating and current tuning allows mode hop free tuning ranges of several 10 GHz.
1. Temperature influences both the optical path length of the laser cavity and the gain curve of the laser diode used. The frequency of the laser diode decreases with increasing temperature. For a laser diode the typical temperature tuning range is 0.06 nm/K ($\cong$ 30 MHz/mK). It can be used for scanning, however, due to the temperature controlling requirements this is only useful for slow scanning of the laser in spectroscopy experiments.

2. Tuning of the frequency of diode laser can be achieved by tilting the angle of the grating. The fine tuning of the tilting angle of the grating can be accomplished with a piezo electric transducer (PZT) element. For our experiments we use the diode lasers in the Littrow configuration (Fig. 3.9). In this configuration, the grating is aligned such that the first order diffraction light returns directly to the laser diode. The amount of light which is fed back is selected by the grating. It ranges from 5-50% depending on the laser diode. The output is the zeroth order reflected beam that can be 50% to 80% of the original output power of the laser diode. The angle at which the incident beam strikes the grating sets the wavelength of the output beam, given by

$$\lambda = 2dsin\theta$$  \hspace{1cm} (3.1)

where $\lambda$ is the wavelength of light, $d$ is the distance between the grooves of the grating and $\theta$ is the angle of incidence with the grating normal. The wavelength tunes with the angle $\theta$. This angle is varied by changing the voltage on the PZT. As the voltage increases, $\theta$ decreases, and the wavelength decreases. The frequency tuning range of the diode laser with PZT is 300 MHz/V. The modulation frequency is limited to $\approx$1.5 kHz due to mechanical resonances of the grating support.

3. Changes of the injection current affect both the diode temperature and carrier density that changes the index of refraction of the active area, which in turn affects the wavelength. Thus the wavelength of the laser can be tuned with the injection current. Increase in the injection current decreases the frequency of the laser diode. Typical tuning range of current is 4 GHz/mA. The modulation frequency of a few hundred MHz can be attained with injection current.

For barium we use diode lasers at 791.3 nm to drive the $6s^2 \, ^1S_0 - 6s6p \, ^3P_1$ transition and to populate the metastable triplet $D$ states (see Section 4.5). To
obtain the long term frequency stability we used iodine (I$_2$) spectroscopy to lock these lasers to a transition in molecular iodine described in the next section 3.3.2.

### 3.3.2 Iodine Spectroscopy

Iodine is a well known secondary frequency standard for frequency stabilization of lasers [91]. Iodine, a heavy diatomic molecule, has a large number of bound ro-vibrational states for each electronic configuration. A thorough description of the diatomic molecular spectra and the nomenclature used in such systems can be found elsewhere [92]. Transitions from the ground state $X^1Σ^+_0$ to the four low-lying excited states $A' ^3Π_{2u}$, $A ^3Π_{1u}$, $^3Π_{2u}$, and $B ^3Π_{2u}$ lie close to the near infrared/visible region of the spectrum (see [93]). The A-X spectrum lies in the near infrared region (from 890 nm to beyond 1.3 µm) and, being relatively weak, is obscured by the stronger B-X spectrum at short wavelengths [94, 95]. The B-X spectrum extends from 500 nm to around 900 nm and has been the subject of our spectroscopic measurements. The transition is allowed by the $0^+ ↔ 0^+$ selection rule and provides a good example of the break down of the $△S = 0$ selection rule in molecules of atoms with high element number. The transition is quite intense giving rise to the violet color of iodine vapor.

In heavy molecules with highly charged nuclei the spin-orbit interaction may be so strong that $L$ and $S$ are not uncoupled by the electrostatic field of the nuclei. The $L$ and $S$ couple to give a resultant $J_a$ which is then coupled to the internuclear axis with a component $Ω\hbar$. The electronic angular momentum $Ω$ and the angular momentum $N$ of nuclear rotation then form the resultant angular momentum $J$. This is known as Hund’s case (c) and is the best representation of the coupling in iodine. The selection rules that apply in this regime are summarized below.

$$ΔΩ = 0, ±1; \ ΔS = 0; \ ΔJ = 0, ±1;$$

$ΔJ=0$ is forbidden for $Ω = 0 → Ω = 0; 0^+ ↔ 0^+, 0^- ↔ 0^-, 0^+ ↔ 0^-$. The selection rule for $J$ gives rise to the familiar $Q (ΔJ=0)$, $P (ΔJ=−1)$ and $R (ΔJ=+1)$ branches. However, if both states have $Ω = 0$ then the $Q$ branch no longer occurs.

Lasers stabilized to iodine transitions are widely used as reliable frequency standards [96–100]. High resolution saturated absorption spectroscopy of molecular I$_2$ hyperfine transitions deliver a natural frequency grid in the 500 nm-900 nm range. The absence of an intrinsic electric dipole moment, leading to extremely small perturbation by external electromagnetic fields as well as the strong and relatively narrow natural linewidth of the hyperfine structure transitions make it
an ideal secondary frequency standard. There are more than 60000 iodine lines, which means that there is about one line for every 5 GHz.

**Experimental setup**

The diode laser used for the iodine spectroscopy is in an extended cavity configuration. The laser diode is a 50 mW (GaAlAs-HL7851G) single-mode laser at 785 nm. The highly divergent light from it is collimated with an aspheric lens (Thorlabs C230TM-B). Around 30% of the output power is fed back by means of a 1200 lines/mm Al-coated reflection diffraction grating (Edmund Optics) placed in Littrow configuration, which is held on a piezo electric transducer that changes the angle of the grating to tune the wavelength of the laser. The laser diode current is controlled by a Thorlabs LDC 201 laser diode driver. The temperature of the laser diode is maintained by a 33 W Peltier element sandwiched between the diode mounting block and the anodized aluminium base plate holding the entire setup. The temperature of the laser diode is measured with an analogue AD590 temperature sensor and it is controlled to drift <1 mK in 1 second with an in house built PID controller. A stable single-mode output beam of power 13 mW at 791.3 nm is achieved by tuning the grating angle with the piezo element, adjusting the injection current and the temperature respectively. The typical operating current of the diode at 13 mW is 122 mA.

The collimated output beam from the diode laser is elliptical in nature. It is made roughly circular ~1.2 mm diameter by an anamorphic prism pair. The circular beam passes through a Faraday isolator (LINOS Model: DL1-1; S. No 449) to minimize the unwanted optical feedback from the optics downstream, which would cause instability of the laser. With the help of a wedge around 8% of the beam is split to the wavelengths meter and to the Fabry-Perot (FP) cavity. The former (High finesse Model: w5/6 UV, 250-1100 nm) measures the wavelength to an accuracy of ±1 GHz. The latter is made of two mirrors of radius of curvature -500 mm that were glued to a cylindrical quartz spacer of length 35 mm with one of the mirrors sitting on a piezo element. It has a Free Spectral Range (FSR) of 3 GHz and a finesse of 750 to observe if the laser is in a multiple frequency mode. Mode matching to the FP-cavity is attained with a lens of focal length 250 mm (f6 in Fig. 3.10) placed at a distance of 300 mm. The transmitted light from the cavity is focussed onto a fast Si-photodiode (Thorlabs FDS010) with a lens of f5 = 50 mm (Fig. 3.10).
Figure 3.10: Set up for the frequency modulation saturated absorption spectroscopy of iodine. Linear \perp linear polarization is used for the probe and pump beams. The pump beam is frequency modulated with an acousto optic modulator driven by voltage controlled oscillator. The signals are detected with a split photodiode.
3.3. Laser Facility at TRIμP

Figure 3.11: Block diagram of the control electronics of the diode laser for frequency modulation saturated absorption spectroscopy.

The Iodine Oven

To stabilize the diode laser frequency at barium atomic transition of 791.3 nm the nearest ro-vibrational transition in I$_2$ is the P(52)(0-15) transition at 791.3 nm. It has a total of 15 lines. The line marked ‘a1’ in Fig. 3.12 is the nearest single component to the barium transition and is blue detuned from it. This transition in I$_2$ could be reached with higher ro-vibrational levels. To populate a high vibrational state, higher temperature is needed. But at higher temperatures the I$_2$ pressure in the cell will be enormous, and study of Doppler-free saturation absorption spectroscopy will not be possible due to collisional broadening of lines. This is solved with a cold finger attached to the I$_2$ cell by the supply of I$_2$ molecules to maintain a low pressure in the cell. Thus, the temperature of the cold finger determines the vapor pressure of the cell, while the wall temperature of the cell determines the fraction of I$_2$ vapor in the vibrational level.

In order to satisfy the above requirement an oven was designed and fabricated capable of reaching temperatures up to 600°C, while a copper tube cooled with a Peltier element acts as a cold finger. The cold finger of the I$_2$ cell is maintained at a temperature of 30°C. The temperature of the oven is measured at the center of the cell using a Thermocoax type K-NiCr thermocouple (41μV/1°C).

Optical Layout and Spectroscopy

The experimental arrangement for the frequency-modulation saturated absorption spectroscopy [101,102] is shown in Fig. 3.10. We use linear $\perp$ linear polarization for the probe and pump beams.
The light from the diode laser after the Faraday isolator is focused with a \( f_1 = 750 \) mm lens. A thick glass blank is positioned in its path to generate two weak probe beams of power less than about 0.5 mW and beam radius of about 0.4 mm is passed through \( \text{I}_2 \) vapor cell (length 540 mm) placed inside the oven. The transmitted strong beam after a lens of focal length \( f_2 = 400 \) mm is directed through a polarizing beam splitter (PBS1) for double passing through an acousto optic modulator (AOM). The double passing is advantageous to maintain directional stability of the laser beam that can otherwise lead to systematic shifts of the peak positions. Further, there are two advantages of modulating the frequency of the laser beam with an AOM instead of the grating angle or modulation of the injection current of the diode. One is the linearity of the scan, since the voltage controlled oscillator (VCO) that determines the AOM frequency has a linear transfer function. Secondly, the scan axis has absolute frequency calibration once the voltage to frequency transfer function of the VCO is known. Also, modulation of the injection current of the laser diode produces amplitude modulation on the signal thus affecting the signal to noise ratio. The block diagram of the diode laser control electronics and frequency stabilization electronics is also shown (Fig. 3.11).

The vertically polarized strong beam is focused using a \( f_3 = 200 \) mm lens, into a 80 MHz AOM (IntraAction MT-IR-80). The separation between the zero order and first order beams is 15 mrad. The zero order beam is blocked with an iris diaphragm. A \( \lambda/4 \) plate is used before the AOM to change the polarization of the retro-reflected beam from the focussing mirror of \( R = -200 \) mm and it could also be used to vary the power of the pump beam by ‘misalignment’. The focussing mirror is placed on a micrometer translation stage to obtain maximum double passing diffraction efficiency by fine adjusting the position of the mirror. The double passing diffraction efficiency thus obtained is about 67%.

Now, the horizontally polarized double passed beam is focussed with a lens \( f_4 = 500 \) mm into the \( \text{I}_2 \) cell giving a 0.4 mm diameter beam in the overlapping region. This frequency shifted double passed beam is the strong ‘pump’ beam for the spectroscopy experiment. The polarizing beam splitter cube (PBS2) is used to superpose the pump and probe beams. The PBS2 is aligned, such that the horizontally polarized pump beam is transmitted directly to overlap with one of the probe beams. The vertically polarized probe beams passing opposite to it, however, are reflected and focussed with \( f_5 = 50 \) mm lens on to a split-photodiode.

The typical power of the pump beam was 6 mW after double passing the AOM, and the beam radius \( w (=1/e \) amplitude radius) in the cell is about 0.4 mm. The frequency modulation signal for the saturation spectroscopy is obtained from
a VCO operated at the center frequency of the 80 MHz AOM by applying a vol-
tage of 0.42 V with a function generator (HP 3314A). The output RF power of the
VCO is +11 dBm. It is attenuated down to -2 dBm with a 13 dB attenuator. The
output of the attenuator is given to a RF power amplifier (Mini-circuits, Model-
ZHL-1-2W), to drive the AOM. The modulation frequency and modulation depth
are controlled by the function generator. The typical modulation frequency is
90.5 kHz and the modulation depth is 4 MHz. The demodulated first derivative
signal of the Lorentzian absorption signal is obtained with a 1-100 kHz lock-
in amplifier (Scitech). The spectrum of the P(52)(0-15) transition measured by
a low-noise split photodiode (UDT sensors model: SPOT-2D). The electronics
circuit diagram of the split-photodiode amplifier is given in the Appendix B.1.

We get a good agreement of the iodine spectrum of the P(52)(0-15) transition
compared with the spectrum generated with a Doppler width of ± 0.0003 cm⁻¹
by commercial software based on the results of [103]. The generated spectrum
is shown in Fig. 3.12. From the resolution of the multiplets we can estimate the
linewidth of the transitions to be less than 10 MHz. The iodine spectrum is used
to stabilize the laser frequency. The shape of the signal is ideal for a locking
application.

The laser frequency is tuned to the line marked ‘a1’ in Fig. 3.12. The deriv-
ative like signal after the lock-in amplifier is given to a servo loop that has two
paths. One is the signal to be fed back to the piezo of the diode laser and the
other is to the injection current of the laser diode. The piezo path consists of a
proportional gain stage and an integrator, which is used to stabilize the frequency
to the zero crossing of the derivative signal. The current path consists of pro-
portional gain amplifier to reduce the low frequency noise. The laser remained
locked for several hours without problems.

The linewidth of the I₂ laser was measured with the amplitude of the error
signal before and after frequency locking the laser that is calibrated in frequency.
It is found that the linewidth of the diode laser after frequency stabilization is less
than 1 MHz. The method used to measure the linewidth of the laser does not pro-
vide a good estimate, but it served our purpose. One can measure the linewidth
and stability of the laser by optical heterodyne measurement. By locking two dif-
ferent lasers to the adjacent single components of the P(52)(0-15) transition, i.e.,
locking the lasers to ‘a1’ and ‘a10’ components and measure the beat frequency
with a fast photodiode. This gives better accuracy for the frequency measure-
ment.
Figure 3.12: (a) The measured hyperfine spectrum of \(P(52)(0-15)\) transition by frequency modulation saturated absorption spectroscopy of iodine. The iodine oven temperature is \(560(10)\)°C. The sensitivity of the lock-in amplifier used is \(300\) µV that corresponds to \(10\) V. (b) The first derivative of the Lorentzian hyperfine spectrum of \(P(52)(0-15)\) transition in iodine [103]. The parameters used are temperature \(T = 560\)°C and hyperfine linewidth = \(0.0003\) cm\(^{-1}\) corresponding to a resolution of 9 MHz for each component.
3.4 TRIμP - Studying Fundamental Interactions and Symmetries

In the new TRIμP facility we can produce rare isotopes like $^{213}$Ra and $^{21}$Na. Both are ideal candidates for fundamental tests of the Standard Model. The separator as a facility has been used for first physics experiments and all the ingredients have been tested. The production target and the magnetic separator are in use by the scientists and user community. In the near future we hope to improve the thermal ionizer. The radio frequency quadrupole cooler and buncher and low energy beam line was constructed and commissioned. We set up a laser facility with the development of diode lasers, electronics for signal control and detection and established iodine spectroscopy as a frequency reference. In conclusion, the combination of all the different stages to a facility will make the research for fundamental symmetries with radium and sodium possible at KVI.