High Precision Measurements on Helium at 1083 nm

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Abstract. We present a review of the helium spectroscopy, related to transitions between 2^3S and 2^3P states around 1083 nm. A detailed description of our measurements, that have produced the most accurate value of the $2^3P_0 - 2^3P_1$ fine structure interval, is given. It could produce an accurate determination (34 ppb) of the fine structure constant α. Improvements in the experimental set up are presented. In particular, a new frequency reference of the laser system has been developed by frequency lock of a 1083 nm diode laser to iodine hyperfine transitions around its double of frequency. The laser frequency stability, at 1 s timescale, has been improved of, at least, two orders of magnitude, and even better for longer time scales. Simultaneous $^3He - ^4He$ spectroscopy, as well as absolute frequency measurements of 1083 nm helium transitions can be allowed by using the I_2-locked laser as frequency standard. We discuss the implication of these measurements for a new determination of the isotope and 2^3S Lamb shifts.

1 Helium and Fundamental Physics

High precision spectroscopy of "simple" atomic systems has been demonstrated to be a powerful tool for measuring quantities in fundamental physics as, for example, fundamental constants [1]. Regarding to the fine structure constant α, since the fine-structure (FS) separations are nearly proportional to $\alpha^2 R_\infty$, accurate measurements of the FS splittings of a "simple" atom can be used to determine α, in case sufficiently precise theoretical predictions of them are available. Relativistic quantum mechanics and QED provide such predictions when applied to atomic or ionic systems as Hydrogen and Helium. Although Hydrogen has been always considered the "natural" candidate for all fundamental constants measurements, here is an exception: in the case of α, more precise results can be obtained with Helium, as was pointed out by V.W Hughes early in 1969 [2]. In fact, from an experimental point of view, wider FS separations and narrower linewidths allow for more precise measurements. The largest FS splitting in Helium ($2^3P_1 - 2^3P_0$) is three times the largest one in Hydrogen ($2^2P_{1/2} - 2^2P_{3/2}$), and the linewidth of the involved levels is sixty times smaller in Helium than

in Hydrogen. This advantage is confirmed by the experimental results: the Hydrogen $2^2P_{1/2} - 2^2P_{3/2}$ separation has been measured to 1.4×10^{-6} from the $2^2S_{1/2} \rightarrow 2^2P_{3/2}$ and $2^2P_{1/2} \rightarrow 2^2S_{1/2}$ transitions [3], whereas $2^3P_1 - 2^3P_0$ separation in Helium has been recently measured by our group with an accuracy of 6.8×10^{-8} [4]. This measurement, together with the recent advances in the QED theory for a two electron-bound system, could provide a 34 ppb precise α value. It could help to clarify the actual puzzling situation of α determinations at the level of 10^{-8} [5], which will be more stringent as more as accurate measurements and predictions of the 2^3P helium level FS will be available. This issue has taken to the development of precise spectroscopic techniques around 1083 nm: the radiative wavelength that links the triplet P level with the triplet S metastable level of Helium (see Fig. 1).

2 Fine Structure of the Helium 2^3P Level: Experiments

At present, five experimental measurements for the 2^3P splittings are available; all but the first [6] are from groups still active and working at helium FS measurements [4,7,8,9,10,11]. Although these experiments use different approaches to measure the fine structure, ranging from microwave spectroscopy in the 2^3P levels [6,9,10] to frequency difference of the $2^3S \rightarrow 2^3P$ optical transitions [4,7,8,11], helium spectroscopy at 1083 nm is always present (see Fig. 1). A detailed description of all related experiments is out of the scope of this paper, and we will confine the discussion to our measurement [4], and briefly, to other measurements to compare with it.

Apart of the sub-MHz spectroscopy of helium fine structure realised by W.E. Lamb Jr. in the late '50s, the first results competitive with the fine structure measurements in hydrogen, were done by V. Hughes and coworkers with a series of experiments that started in the late '60s and continued for more than a decade [6]. The experimental approach followed was a magnetic-resonance atomic beam technique. To circumvent the low quantum efficiency of fluorescence detection, the magnetisation variations induced by the microwaves were directly observed with a double Stern-Gerlach selector followed by an atom detector. Indeed, since the 2^3S metastable state carries an internal energy of about 20 eV, metastable helium atoms can be detected with a quantum efficiency close to unity. The preparation in the 2^3S level with a well-defined magnetisation was obtained by a trajectory selection operated after the passage through a magnetic field gradient. Then, atoms were excited to the 2^3P level by a discharge lamp and were simultaneously illuminated by the microwave field causing a magnetisation variation. A second magnetic selector allowed only the desired atoms to impinge on the atomic detector. In these experiments the main issues were related to the presence of the bias magnetic fields of 10 to 200 mT: a remarkable work has been done both to assure the necessary stability and homogeneity and to have an accurate calibration of the intensity in the interaction region. The lineshape distortion, consequent to the way the resonances were sweeped (i.e. by fixing the microwave frequency and varying the magnetic field), and the second order

Zeeman shift required a careful analysis, so that also the $2^3P, G_J$ was measured. V. Hughes and collaborators measured all the three intervals separately, since the mixing of FS levels induced by the magnetic fields allowed even $\mathcal{J} = 2$ to $\mathcal{J} = 0$ transitions (we note as $\mathcal{J}$ a level that connect to the J manifold at zero magnetic field). Their published results have been recently modified by taking into account better the systematic effects due to the strong magnetic fields [12].

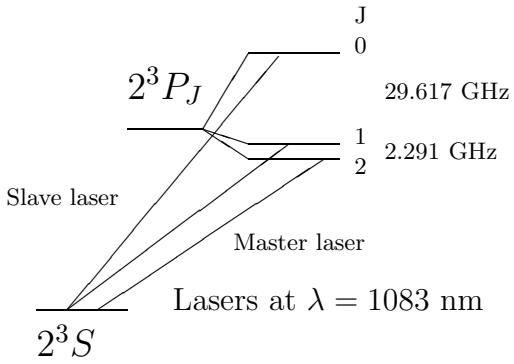

Fig. 1. Scheme of helium energy levels relevant for our experiment

A completely different approach was taken in a recent experiment, completed in 1995 at Yale University [7]. The development of laser spectroscopy made advantageous to go back to FS measurements in the optical domain, i.e. as frequency differences of optical transitions. Shiner and coworkers measured the wavelength of the different FS components of the 1083 nm $2^3S \rightarrow 2^3P$ transitions. The detection scheme was again based on a double Stern-Gerlach apparatus, but the demagnetisation was caused by the laser beams. The major source of uncertainty was attributed to the interferometric technique employed to measure the laser wavelength. Recently, the experiment has been modified to avoid wavelength calibration problems: a side-band spectroscopic technique has been used to measure directly the frequency separation of the smallest 2^3P splitting [8]. In this way, the accuracy for this interval has been improved by a factor of 3 with respect to the previous results, where the uncertainty now being was mainly attributed to the systematic effects from the moderate magnetic fields used.

At York University, Toronto, microwave measurements have been revived by Storry and Hessels [9,10], that could benefit of lasers to excite the 2^3P level, instead of the lamps used by Hughes and coworkers. Also, the detection of laser-induced fluorescence from 2^3P levels makes another basic difference with respect to Hughes experiments, which, together with a microwave frequency scan, eliminated the lineshape asymmetries. In this experiment, a moderate magnetic field is also used to select the transitions between the desidered M_J sublevels. The

final uncertainty was mainly limited by the effect of the out-bound microwave power in the region of the laser excitation.

Finally, we wish to mention that, at Harvard University, another laser spectroscopy experiment was carried out in a discharge cell, and not in a "clean" environment as the metastable helium beam of the other experiments. The uncertainty of this unpublished measurement is 8 kHz [11], probably due to systematic effects from collisions in the helium cell [13].

2.1 The Florence Experiment

In Florence, we have chosen an approach that combines laser spectroscopy with the direct frequency measures of the microwave experiments [4]. We take advantage of the obvious consideration that to obtain the FS separations there's no need to precisely know the optical transitions frequencies but just their differences. Thus, if we have two laser frequencies whose difference can be accurately controlled, we may use one as a fixed reference and tune the second across the atomic resonances, as illustrated by Fig. 1. In fact, our approach reverts to an heterodyne technique, where all the transitions are measured with respect to the same reference frequency, that can take any arbitrary but stable value. In the experimental realisation we obtain the two frequencies by phase-locking two diode lasers (master and slave), i.e. phase-locking their beat note to a microwave oscillator [14]. We show in Fig 2 a full-view of the experimental set-up.

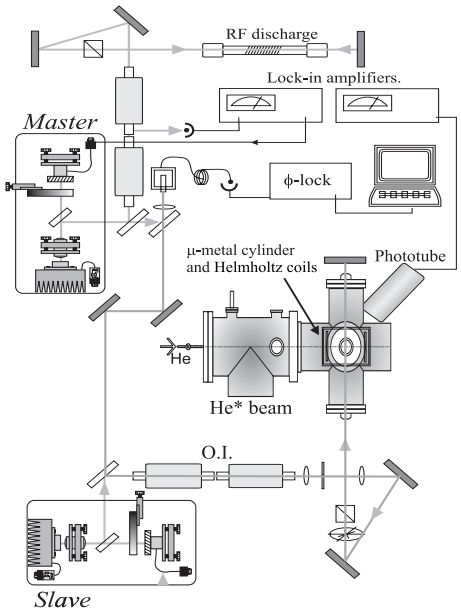

Fig. 2. Experimental set-up for high precision helium spectroscopy

Diode lasers are very compact and convenient sources, although their emission is generally broader in frequency than the one of solid state lasers, it can be narrowed by reflecting part of the emitted light back into the laser chip. This widely adopted technique, named "optical feedback", is implemented by mounting in front of the diode laser a partially reflecting element, such as a beam splitter or a diffraction grating (extended-cavity configuration). Fig. 3 (*a*) shows quite clearly the effect of the optical feedback, where the linewidth was reduced by one order of magnitude ($\tilde{3}00$ kHz) with a 50% of feedback. The master laser (i.e. the reference frequency) was locked on $2^3S_1 \rightarrow 2^3P_J$ transitions, detected by saturation spectroscopy in a cell where the metastable helium was produced by means of a radio-frequency discharge. The reference transition was the one not related to the 2^3P splitting to be measured (see Fig. 1). The measured frequency stability with this system was 5×10^{-11} in 1 s. A detailed description of the two diode lasers phase-lock, lying outside the scope of this paper, can be found in Ref. [14]: here, we report only the measured root Allan variance of the frequency difference, $0.1 \cdot \tau^{-1/2}\sqrt{\text{Hz}}$, and the power spectrum of the beatnote between the two phase-locked lasers (see Fig. 3 (*b*) showing a 1 MHz lock bandwidth).

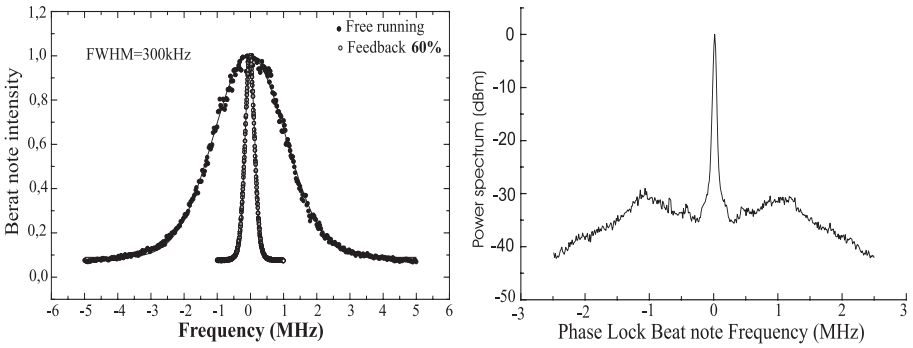

Fig. 3. (a) Spectral power density of the beat note between the extended-cavity master laser and the slave laser, with or without optical feedback; (b) Spectral power density of the beat note between the two phase-locked diode lasers

We detected the saturated fluorescence emitted by a beam of 2^3S metastable atoms as they cross at right angle the slave laser light. A 10^{15} atoms/s.sterad flux of metastable helium atoms was produced by electronic collisions in a DC discharge of a helium atomic beam, similar to that described in [15]. To improve the precision of the linecenter determination, we increased the signal-to-noise ratio S/N by means of standard frequency modulation: the third harmonic demodulated lineshape is shown in Fig. 4. The function expected for a Lorentzian spectrum was fit and linecenters were calculated with an uncertainty ranging between 10 kHz and 20 kHz, that is consistent with the observed S/N, mainly limited by the stability of the reference frequency and of the metastable helium beam. The reproducibility was two or three times worse than the uncertainty,

where to randomize the linear drift of the reference laser (about 60 kHz/h), the two 1083 nm helium transitions were recorded alternatively, and only their frequency differences were averaged. The average of about 200 differences improved the statistical uncertainty to about 2 kHz.

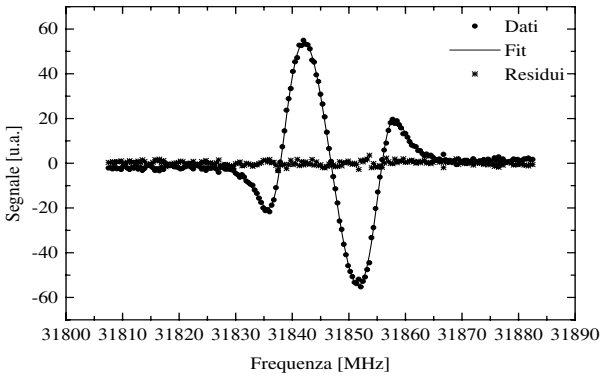

Fig. 4. Third harmonic demodulated signal of the $2^3S_1 \rightarrow 2^3P_2$ transition, fit to the expected function

Perhaps, the most significant difference with respect to previous experiments is that no bias magnetic field is present: a cylinder of high magnetic permettivity metal (mu-metal) embeds the interaction region to shield it against dc and ac magnetic fields while a couple of Helmholtz coils inserted therein allow for the fine cancellation. In general, by selecting the transitions connecting $m = 0$ states, the first order Zeeman effect is (in principle) eliminated but at the current level of accuracy even the second order effect is relevant: e.g. the separation between $2^3P_0\, m = 0$ and $2^3P_1\, m = 0$ decreases by 0.18 MHz in a field of 3 mT. Moreover, in our experience a magnetic field transverse to the laser polarisation of 16 μT gave rise to a 0.05 MHz shift of the measured ν_{01} separation. This shift is too large to be explained by simply admitting a linear Zeeman shift combined with the residual ellipticity of the laser polarisation. As a consequence, we choose to work with zero magnetic field. To minimise it *in situ*, we made use of the non-linear Hanle effect: in presence of optical pumping toward non-coupled sublevels of the ground state, the fluorescence signal drops, unless a magnetic field recycles the sublevels populations. Thus, we tuned the Helmholtz coils current in search for the minimum of signal. We then measured the magnetic field to be below 0.1 μT in a cube of 1 cm^3 around the interaction region. The related systematic error, with the conservative assumption that it scales linearly with the residual field, is less than 0.3 kHz.

Surprisingly, however, we found that the major limitation to our experimental accuracy was due to the recoil imparted by photons to atoms. The radiation forces are of course well-known, being used for laser cooling, nevertheless their effect in precision spectroscopy is often disregarded as the interaction time be-

tween light and particles is short. However, we found that these forces cause a lineshape asymmetry and a consequent shift of the linecenter [16]. We can understand at least the origin of this shift with simple qualitative arguments, while for a precise characterisation a numerical analysis is required.

Basically, the shift occurs because the velocity and position distribution of atoms is modified by the interaction with the laser light. In our experimental configuration, the laser was arranged in a standing wave with two linearly-polarized, counterpropagating beams, shined orthogonally to the atomic beam. Let's consider what happens when the laser is detuned below resonance (red detuning). The velocity-dependent component of the force is damping, therefore the transverse velocity distribution of the atoms is cooled. Since the saturated fluorescence we detect is proportional to the number of atoms which have nearly zero transverse velocity, cooling yields an increase of the signal. Moreover, in the standing wave the position-dependent component of the force pushes the atoms toward the high intensity region, i.e. the antinodes, leading to a further increase of the signal. The opposite occurs for blue-detuning. For cycling transitions, the number of photons scattered by any atom is limited only by its transit time across the laser beam: in our experiment, the shift of the cycling $2^3S_1 \rightarrow 2^3P_2$ line was of the order of 0.2 MHz, about one tenth of the natural width. On the other hand, the $2^3S_1 \rightarrow 2^3P_J$ $(J = 0, 1)$ are "open" transitions, i.e. transitions for which the selection rules make at least one of the Zeeman 2^3S sublevels uncoupled to the laser light ("dark" levels). For these two transitions optical pumping toward dark levels reduces the number of scattered photons and, as a consequence, the lineshift turns out to be almost one order of magnitude smaller. Furthermore, we take advantage of the partial cancellation in the frequency differences. For the FS experiment, we implemented a numerical solution of the optical Bloch equations and, after we verified that the predicted shifts were in agreement with the observed values for different interaction times [16], we corrected our $2\,^3P_0 - 2\,^3P_1$ measured value by 11.7(9) kHz. Our final results (line 3 of Table 1) clearly show how the obtained accuracy depends on whether or not the closed transition $2^3S \rightarrow 2\,^3P_2$ enters the measured interval.

2.2 State of the Art of the 2^3P Helium Splittings

The most recent results of the 2^3P splittings for all experiments indicated above are summarised in Table 1, and graphical comparison of the measurements for the $2^3P_0 - 2^3P_1$ separation is shown in Fig. 5. Also the most precise theoretical determinations are included in this table [17,18,19]. The theoretical values of the FS splittings are given by difference of the energy of the levels involved, which is calculated by means of power series perturbation expansion of the fine structure constant α, where the non relativistic terms are used as zero-order, i.e. unperturbed Hamiltonian. Since the non relativistic eigenvalues are known within 1 part in 10^{15}, relativistic and QED small corrections must be considered when a ppb accurate determination of the FS splittings is required. They are calculated by means of a perturbation procedure, where the problem is twofold: (1) find the approximate eigenfunctions of the unperturbed Hamiltonian, (2)

Table 1. Measurements and the theoretical predictions of the $2^3P_1-2^3P_2(\nu_{12})$, $2^3P_0-2^3P_1(\nu_{01})$ and $2^3P_0-2^3P_2(\nu_{02})$ FS intervals of helium. For each splitting, the differences with the most accurate measurement are indicated

	ν_{12}		ν_{01}		ν_{02}	
Groups	$\Delta\nu_{12}$	D	$\Delta\nu_{01}$	D	$\Delta\nu_{02}$	D [1]
Hughes [12]	196 (5)	+20.1(5.1)	864 (33)	−85.7(33.1)	40 (20)	−95 (20)
Shiner [7,8]	175.9 (1.0)	—	962 (3)	+12.3 (3.6)	135 (3)	—
Inguscio [4]	174 (15)	−1.9(15.0)	949.7 (2.0)	—	121 (15)	−14 (15)
Storry [9,10]	174.0 (1.4)	−1.9 (1.7)	966 (13)	+16.3(13.1)	140 (13)[2]	+5 (13)
Gabrielse [11]	198 (8)	+22.1(8.1)	936 (8)	−13.7 (8.2)	134 (8)	−1 (9)
Drake 1 [17]	180 (12)	+4 (12)	949 (15)	−0.7 (15.1)	129 (19)[2]	−6 (19)
Drake 2 [18]	179.9 (10)	+4 (10)	974.1 (10)	+24.4(10.2)	154 (15)[2]	+19 (15)
Pachucki [19][3]	173.6 (0.5)	−2.3 (1.1)	949.6 (0.2)	−0.1 (2.0)	123.2 (0.5)[2]	−11.8(3)

(1) $\nu_{12} = \Delta\nu_{12}+2\,291\,000$, $\nu_{01} = \Delta\nu_{01}+29\,616\,000$, $\nu_{02} = \Delta\nu_{02}+31\,908\,000$; D: Difference with respect to the most accurate measurement; all values in kHz; errors are one standard deviation

(2) From $\nu_{12}+\nu_{01}$

(3) Only computational errors have been considered (see text)

work out the perturbation operators. Nowadays, the calculus of the eigenfunctions is a well solved problem for Helium; instead, the determination of some high order perturbation operators remains the limiting factor of the energy level calculus. In fact, the current state of the art of the perturbation operators for Helium is in the terms of the order $O(mc^2\alpha^7)$ for both theoretical determinations tabulated here [18,19]. For completeness, we have also reported another determination from the Drake group [17], where the corrections of the $O(mc^2\alpha^7)$ order are not included at all, and the calculus is stopped at the $O(mc^2\alpha^7\log\alpha)$ order. A description of these theoretical determinations is given in other contributions of this volume, and we refer to them for details. We only indicate that the errors of Drake's group determinations were calculated considering all the high order terms not included in the calculus, whereas for the Pachucki's group determinations the error was only computational.

The most precise value for the smallest splitting ν_{12} is given by the recent Shiner's group measurement [8], but it is still discrepant (one error bar) with the other kHz level accuracy value [10]. Anyway, these measurements have improved by a factor of 3 the previous most precise value [7], and they can be used to test the QED theory for the Helium 2^3P fine structure, since the predictions are still more than one order of magnitude less accurate. A larger discrepancy can be observed for the ν_{01} splitting, where the most accurate value at 2 kHz level is given for our measurement [4]. There is more than 3 error bars of disagreement with respect to the values with the next accuracy [7,11], but it is very close to the weighted mean of all experimental measurements, as is shown in Fig. 5. It

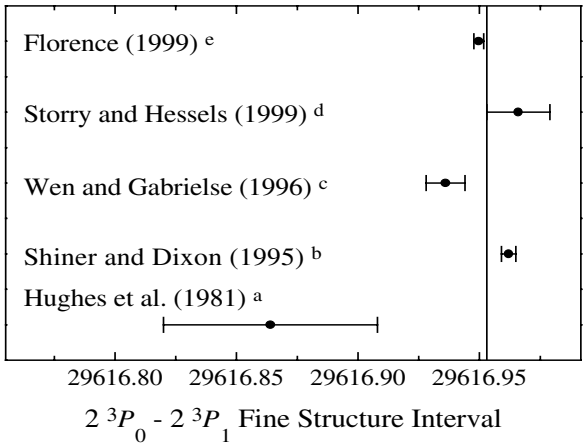

Fig. 5. Measured values of the $2^3P_0 - 2^3P_1$ interval and their weighted average; a: Ref. [12], b: Ref. [7], c: Ref. [11], d: Ref. [9], e: Ref. [4]

is worthing noticing the concordance of our value with two of the theoretical predictions [17,19], but the discrepancy with the third one [18] is an indication that all the $O(mc^2\alpha^7)$ contributions must be calculated to claim a 10^8 accuracy for the FS predictions. When this problem will be solved, a 34 ppb accurate value of the α constant could be determined from the Helium FS. Finally, with respect to the third interval ν_{02}, a kHz level accuracy measurement doesn't allow more precise determination of α with respect to the ν_{01} interval, but it can be used to test the consistency of the measurements of the other two intervals.

3 Hyperfine Iodine Transitions at 541 nm: a New Frequency Reference for Helium Spectroscopy

To further improve the accuracy of our FS measurements, the frequency stability of the master laser and the S/N of the 1083 nm helium transitions must be increased. In this way, not only the statistical uncertainty will be improved, but it will also allow a precise experimental check of systematic effects.

The lack of accurate and stable frequency standards in the near-infrared spectral range, and in particular at 1083 nm, is a serious inconvenient to improve the present frequency stability of the He-locked master laser. On the other hand, hyperfine transitions of the iodine molecule has been defined as secondary frequency standard at different visible wavelengths, and in particular at 532 nm, the doubled frequency of the 1064 nm Nd:YAG laser. Likewise, our idea has been to lock the master laser frequency to I_2 hyperfine transitions at its doubled frequency, 541 nm.

By means of second harmonic generation (SHG), we have developed a new laser source at 541nm: a single pass, periodically-poled $KTiOPO_4$ (pp-KTP)

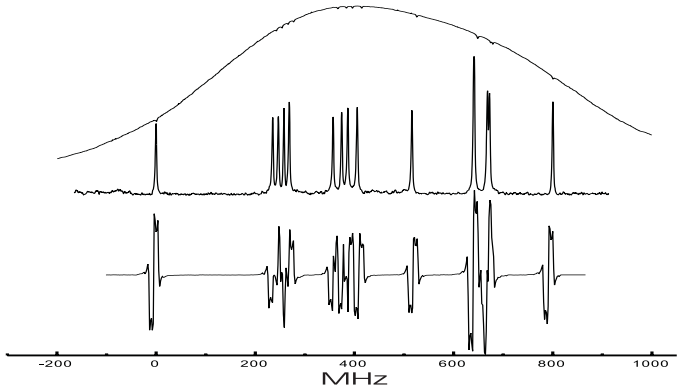

Fig. 6. Direct absorption, AM and FM spectra of the hyperfine components of the B–X R(34)27-0 transition of I_2 at 541 nm. Note the hyperfine Lamb-dips are observed in the absorption spectrum

crystal injected by a 30 dB fiber amplified diode laser emitting at 1083 nm [20]. This is an efficient way to obtain up to 6 mW of stable green power, easily tunable in a 1.2 THz range around 541 nm, that overcomes the problems of the low output power of diode lasers and those of amplitude stability and tunability that plague the enhancement doubling cavities. Moreover, we have measured that frequency and amplitude noise are not added to the amplified radiation by the Yb-dopped fiber amplifier [21]. The generated green power is used to perform sub-Doppler saturation spectroscopy of hyperfine iodine transitions in a classical pump-probe configuration. In Fig. 6, we show the direct absorption spectrum of the B–X R(34)27-0 I_2 transition, where the hyperfine Lamb-dips can be observed. It demonstrates the high amplitude and frequency stability of our system. To isolate the hyperfine signals from the Doppler background and to increase the S/N ratio, different modulation techniques, and consequent experimental set-up have been used . Fig. 6 shows the result of two of them: the amplitude modulation (AM) and frequency modulation (FM) spectra. The AM spectrum has been used to spectraly characterise the hyperfine transitions, whereas the FM spectrum has been preferred to frequency lock the master diode laser at 1083 nm. The FWHM of the hyperfine transitions was about 1.2 MHz, mainly limited for the laser linewidth in the green and for the pressure broadening at 50×10^{-3} Torr (iodine vapor pressure at 8 ^{o}C). These conditions maximised the S/N of the iodine signals.

To characterise its frequency stability, we have measured the root Allan variance $\sigma(\tau)$ of the two identical I_2 locked lasers [22]. A complicate experimental arrangement allowed us to use the same fiber amplifier and crystal for both sources. A stability value of 1.9×10^{-12} in 1 s (corresponding to 540 Hz at 1083 nm) is achieved, which improves to 4.1×10^{-13} at 300 s (see Fig. 7). In

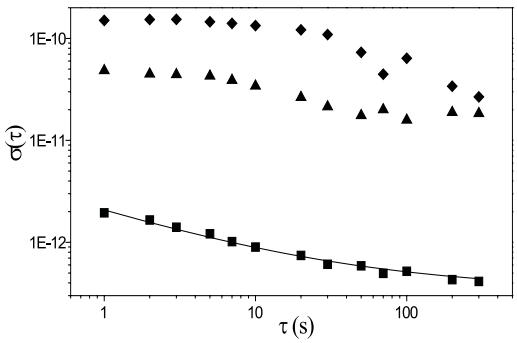

Fig. 7. Allan variance $\sigma(\tau)$ of the beat signal between two DBR diode lasers at 1083 nm: ♦ He-locked lasers, ▲ one He-locked laser and one I_2-locked laser, ■ I_2-locked lasers, fitted with a $1.74(6)10^{-12}\tau^{1/2} + 3.4(3)10^{-13}$ function

view of its main application, we measured a root Allan variance stability improvement by a factor 75 at 1 s and more than 100 at longer time scales, when the I_2-locked were used, with respect to the Helium reference. Moreover, the long-term drift of 57 kHz/h of the He-locked lasers, evident in the middle trace of Fig. 7, is also avoided for the I_2-locked lasers.

We have obtained preliminary results in helium spectroscopy by using a I_2-locked master laser. In Fig. 8, the relative frequencies of helium transitions with respect to the I_2-locked master frequency (full circles) are shown. Similar results (empty circles), when the master laser was He-locked, are also reported to compare with the previous situation. In both cases, a frequency offset of about 13300 MHz and 2200 MHz, respectively, has been subtracted to report all values around zero in the vertical scale. We can observe that the uncertainty of a single measurement has been improved by a factor of 2 and the time spread of a set of measurements by a factor of 5 for the smallest S/N ratio transition ($2^3S \rightarrow 2\,^3P_0$), confirming the previous limiting role of the reference frequency in the final accuracy. Moreover, the frequency drift, clearly observed for the $2^3S \rightarrow 2\,^3P_1$ transition (He-locked case), is not present any more when the master laser is I_2-locked, confirming the result obtained with the Allan variance analysis. As a consequence of these results, a 1 kHz statistical uncertainty for the FS intervals is achieved with less than 20 averages, instead of the 200 necessary before. Moreover, the average can be now performed directly on the 1083 nm transitions, and then used calculate the FS splitting by difference of the average values. In fact, we have controlled that the result of the ν_{01} by using the few new measurements showed in Fig. 8, is the same both with this new and with the old average procedures.

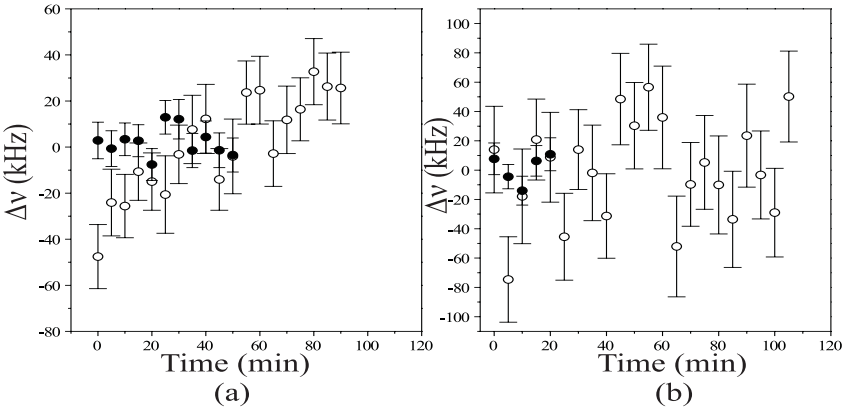

Fig. 8. Time evolution of the relative frequency of the $(a)2^3S \rightarrow 2\,^3P_1(\nu_1)$ and $(b)2^3S \rightarrow 2\,^3P_0(\nu_0)$ transitions of helium at 1083 nm with respect to the master laser frequency (ν_m), alternatively locked on the $2^3S \rightarrow 2\,^3P_2$ helium transition in a RF discharge cell ($\circ$ points), or on one hyperfine component of the B-X P(105) 29-0 I_2 line ($\bullet$ points). $\Delta\nu = (\nu_{1,0} - \nu_m) - 2291.35987\ MHz$ for $\circ$ points, and $\Delta\nu = (\nu_{1,0} - \nu_m) - 13319.69872\ MHz$ for $\bullet$ points. The error bars are one standard deviation of the fit (see text)

4 Conclusions and Final Remarks

In this paper, a review of precision spectroscopy measurements of the fine structure of the 2^3P level of helium has been reported. In particular, we describe our experiment, that has produced the most accurate result for the $2^3P_1 - 2^3P_0$ splitting. Actually, this value could produce a 34 ppb accurate determination of the fine structure constant, if a similar accuracy prediction of the splitting would be available. This figure can be improved by increasing both experimental measurements and theoretical predictions. This issue is addressed by several groups: the groups refered in [4,8,10,11] for the experiment, and the groups of [18,19] for the theory. In this sense, our experiment has been improved by introducing a new frequency reference: the hyperfine iodine transitions around the doubled 1083 nm frequency. We have presented here the frequency stability improvements of our apparatus with this new reference, as well as the benefits in the Helium spectroscopy that it has produced.

Moreover, the tunability of the developed "green" laser and the rich density of I_2 absorptions give a grid of frequency references at 1083 nm as we show in Fig. 9. It can be used for other frequency difference measurements, such as ^{3}He hyperfine splittings and ^{3}He-^{4}He isotope shifts. This shift is large enough to allow a precise determination of the relative nuclear radii of these atoms, and it is also used to test QED corrections [23]. But, perhaps, the most important advantage of the new reference, is the possibility of absolute frequency measurements of

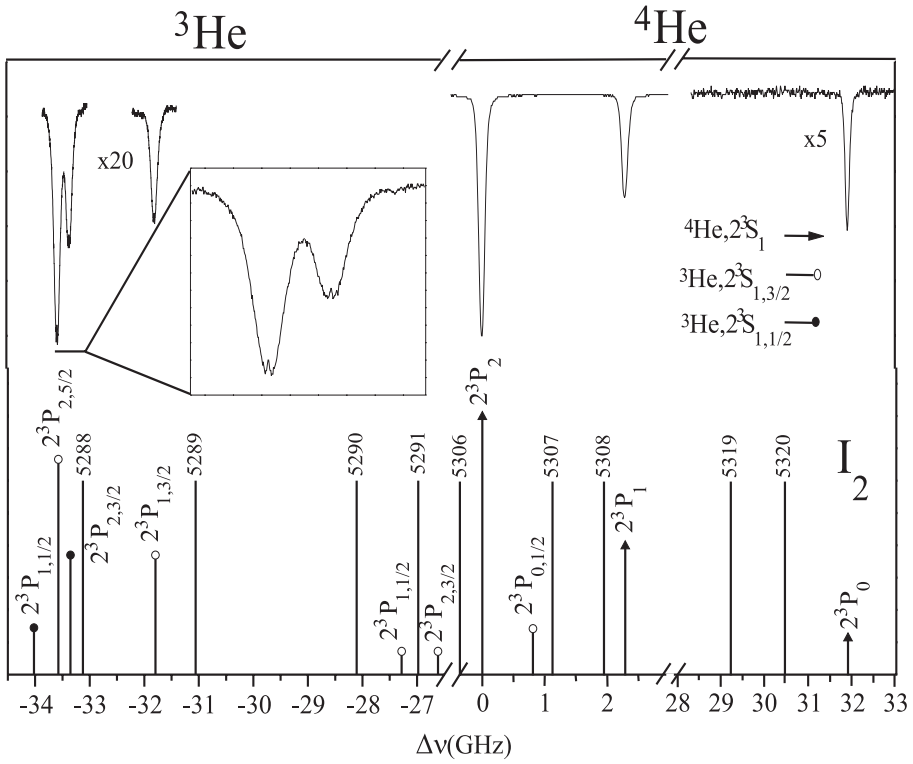

Fig. 9. Coincidence between twice the frequency of ^{3}He and ^{4}He lines and the I_2 spectrum

the 1083 nm helium transitions at 1 kHz accuracy level, thanks to new optical frequency combs [24]. In this way, accurate determination of the 2^3S Lamb-shift can be obtained to test the recently calculated $O(mc^2\alpha^5)$ and higher order QED contributions to the helium energy levels [19,23].

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