Transitions in Muonic Helium Ions Induced by Laser Radiation

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An apparatus to perform a laser-stimulated 3D-3P transition in muonic helium ions (at the Single Burst Extraction Beam of the Brookhaven National Laboratory Alternating Gradient Synchrotron) is presented together with some results.

Some years ago, at the CERN Synchro-cyclotron, a CERN-Pisa Collaboration [1] devised an experimental scheme to perform a laser-induced transition experiment on a muonic helium ion $(\mu^{-4}He)_{2S}$. At that time a rather complex set-up, intimately connected with the operation of the Synchro-cyclotron itself, was installed and made to work, and the energy level differences D_i = 2S - 2P (see Table 1) were measured with an accuracy of 1.5 x 10^{-4}. In Table 1 are presented the experimental results as well as the expected theoretical values as given by the quantum electrodynamics (QED) calculations [2]. As can be seen from the table, the quantities D_i (quantities directly measured) are essentially due to the polarization of the vacuum of the electron-positron field and demonstrate a well-known fact, that the situation for muonic atoms is quite different from that for 'normal atoms' where the vertex corrections to the differences D_i are usually dominant; one concludes therefore that the muonic atoms are the ideal systems to 'check', with significant accuracy, the QED vacuum polarization corrections to the energy levels of bound systems.

However, it is important to note from the table that about 20% of D is, in this case, due to corrections induced by the nuclear electric form factor $\langle r^2 \rangle^{1/2}$: consequently, one can look at the experimental results of Table 1 from two points of view.

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Table 1

Contributions to the n = 2 energy splittings in the $(\mu^{-4}He)^{+}_{2S}$ system

Contributions	Transition energies (meV)	
	$2P_{3/2}-2S_{1/2}$	$2P_{1/2}-2S_{1/2}$
Dirac contribution with Coulomb potential and point-like charges	145.70	0
Nuclear polarizability	3.1 ± 0.6	3.1 ± 0.6
Finite size	-289.5 ± 2.8	-289.5 ± 2.8
Electronic vacuum polarization		
Uehling term: first iteration	1664.44	1664.17
higher iteration	1.70	1.70
Kallen-Sabry term $(\alpha^2 Z\alpha)$	11.55	11.55
$\alpha(Z\alpha)^n$, n > 3	-0.02	-0.02
$\alpha^2(Z\alpha)^2$	0.02	0.02
Muon vacuum polarization	0.33	0.33
μ-e vacuum polarization	0.02	0.02
Hadron vacuum polarization	0.15	0.15
Vertex corrections and (g-2)		
$\alpha(Z\alpha)$	-10.52	-10.85
$\alpha(Z\alpha)^n$, n > 1	-0.16	-0.16
α^2 Zα	-0.03	-0.03
Recoil terms		
Breit	0.28	0.28
Two photons	-0.44	-0.44
Weak contribution	0.00002	0.00002
Sum theory	1526.6 ± 2.8	1380.3 ± 2.8
Experiment	1527.5 ± 0.3	1381.3 ± 0.5

Firstly, one can assume the QED computations to be valid (at least to experimental precision) and deduce with great accuracy from the data the helium nuclear electric form factor, as seen from a muon probe. One obtains:

$$\langle r^2 \rangle^{1/2} = \langle r_\mu^2 \rangle^{1/2} = (1.673 \pm 0.003) \text{ fm} .$$

Comparison of this value with the one obtained from electron-helium nucleus elastic scattering experiments [3] can define the limits of a possible muon-hadron anomalous interaction [4,5].

The value for $\langle r^2 \rangle^{1/2}$ given above represents the most accurate form factor of a nucleus.

Secondly, one can assume for the form factor the existing experimental value $\langle r_e^2 \rangle^{1/2} = (1.676 \pm 0.008)$ fm [3] (as seen by an electron probe), assume muon-electron universality, and then give a limit within which the QED vacuum polarization contribution is 'tested' by these measurements. In doing this, one can see that such a QED correction is tested (at the momentum transfer implied by the experiment) to the level of 0.17%; the result of this experiment represents to my knowledge one of the best direct tests, so far performed, of a vacuum polarization correction.

It is interesting to note that in this last case the limitation in the test is not given by the experimental uncertainties on the energy level differences shown in Table 1, but rather by the experimental uncertainty of the assumed helium form factor.

A CERN-Columbia Collaboration [6] [assisted by staff of the Alternating Gradient Synchrotron (AGS) Brookhaven National Laboratory] have looked into the possibility of performing an experiment of the same type (i.e. via laser transition in muonic ions), but with transitions between levels not belonging to S states in order to avoid the consequences of the electromagnetic form-factor uncertainties.

In particular, this Collaboration has installed a set-up to measure the 3D-3P energy level differences in the muonic helium ions and here I wish to describe the apparatus, its performance, and give some of the experimental results obtained with it.

In Fig. 1 are shown the first energy levels of the muonic helium ion together with some of their characteristics [6]; in the same figure, the transition $3D_{5/2}$-$3P_{3/2}$, which is the first one to be measured, is marked with an arrow.

The principle of the experiment is to see an increase in the K_β intensity due to laser-stimulated transitions when negative muons are stopped in the helium gas present in a multipass optical cavity, where a high-density electromagnetic radiation of the correct wavelength is stored; it is crucial here that the lifetimes of the levels in which one is interested are around 10^{-12} s (we recall that the negative muon cascade time is about 1 ns or less).

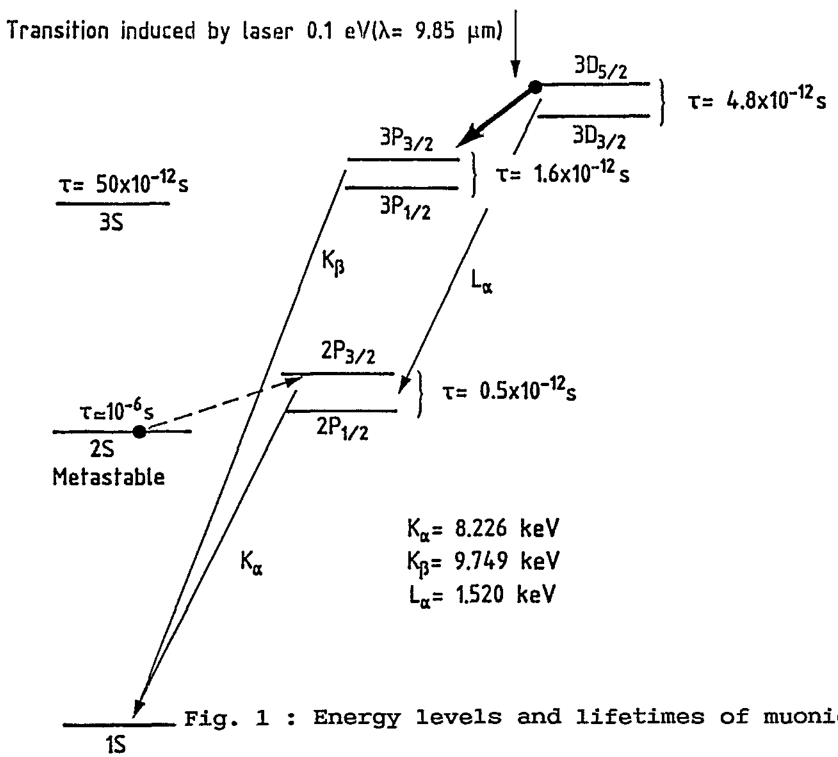

Fig. 1 : Energy levels and lifetimes of muonic helium ions.

From a simple cascade calculation model it can be shown that about 60% of the muons stopped in the target will pass through the D levels: of course, the natural emission of K_β X-rays, during the cascade of the μ^-, represents our main physical background, from which we have to sort out the small increase due to the laser-stimulated emission.

In Table 2 are presented the results of a calculation [6] for the different energy differences 3D-3P; one sees that the wavelength of the radiation to match the resonance conditions is around that of a CO_2 laser and that the width Γ of the lines is 0.437 μm (as deduced from Fig. 1).

It can easily be shown that if N_d is the number of negative muons present in a D level of a helium muonic ion $(\mu^{-4}He)^+_D$ and E/V is the energy density of the radiation at the site of the stopping muon, then the fraction of transitions is given by ($\nu = \omega/2\pi$ is the radiation frequency):

$$\varepsilon = \frac{N_{stim}}{N} = \frac{\Gamma/2}{\hbar^2(\omega-\omega_0)^2 + \Gamma^2/4}\,\frac{1}{\gamma_{3D}}\,|F_{3D-3P}|^2 , \qquad (1)$$

where $\Gamma = (\gamma_{3D} + \gamma_{3P})$ is the width of the transition, γ_{3D} and γ_{3P} are the radiative decay rate of the D and P levels (see Fig. 1; $\gamma = h/\tau$), and $|F_{3D-3P}|^2 = 2.43\,(ea_\mu)^2(E/V)$ is the square of the electric dipole transition matrix element.

Taking V = 0.4 l and E = 4 J in Eq. (1), at the resonance frequency we get : ε = 0.6%. (One of our problems has been to make the volume V as small as possible without losing μ^--stops in the illuminated region and also to limit the background events due to μ^--stopping in regions seen by the X-ray detectors but not illuminated by the radiation of the cavity.)

Figure 2 is a sketch of the target set-up: the effective target is represented by a multipass optical cavity [7] (the mirror surfaces are polished copper), where a CO_2 laser burst is stored (for about

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Table 2

Contributions to the 3D-3P energy level differences

Transition	Vacuum polarization α (Uehling-Serber) (meV)	Vacuum polarization α^2 (Kallen-Sabry) (meV)	Fine structure (Dirac) (meV)	Hyperfine structure (meV)	Total (meV)	λ (μm)
$3D_{3/2}-3P_{1/2}$	110.458	0.905	43.164	0	154.528	8.0235
$3D_{5/2}-3P_{3/2}$	110.458	0.905	14.388	0	125.751	9.8595
$3D_{3/2}-3P_{3/2}$	110.458	0.905	0	0	111.363	11.1334

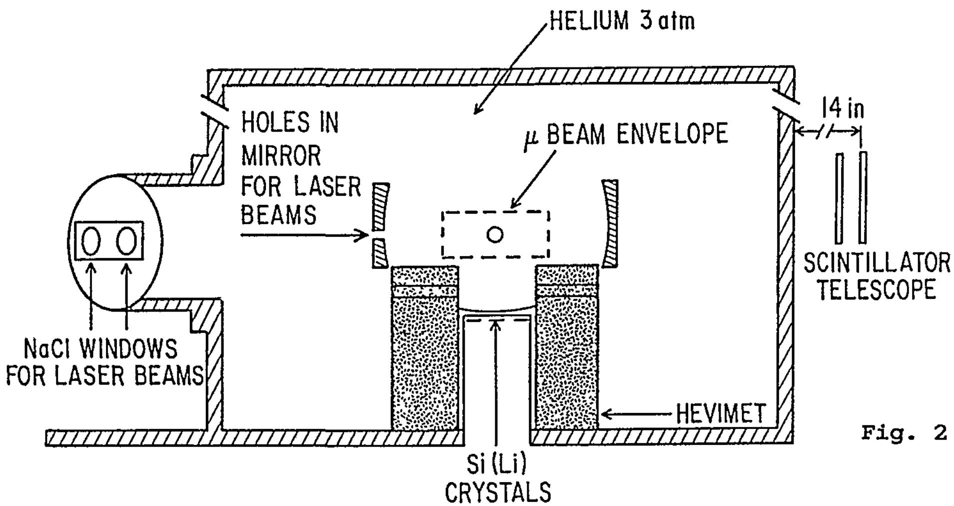

Fig. 2 : Elevation of target box.

100 ns); the cavity is assembled in 3 atm of helium, and in the small-cavity region a burst of negative muons is stopped during the presence of the radiation. At the bottom the K X-ray detecting system is visible; it is composed of 3 Si-Li detectors (2 cm^2 each) situated at about 3.5 in. below the axis of the target cavity.

The cavity assembly is mounted inside a large box filled with 3 atm of helium gas (at room temperature) and the laser beam, split into two parts of about 2 J each (because of the breakdown threshold of the helium gas), enters the box through the NaI-salt windows shown on the left side of the figure. Each beam stays in the cavity for 32 reflections and then exits: the outcoming radiation beams are then used for monitoring and controlling purposes.

To obtain the desired total of 4 J at the correct wavelength, an isotopic $^{13}C^{18}O_2$ laser had to be employed. The laser scheme used is shown in Fig. 3. The oscillator consists of a Transverse Excitation Atmospheric (TEA) $^{13}C^{18}O_2$ laser with a diffracting grating to select a particular frequency (Fig. 4 shows the P branch lines of a $^{13}C^{18}O_2$ laser compared with the expected muonic transition line) in order to explore the entire region of the $3D_{5/2}$-$3P_{3/2}$ transition: one should be able to locate the centre of this resonance to better than 10 Å. Afterwards, the beam from the oscillator passes twice through another $^{13}C^{18}O_2$ TEA laser that functions as an amplifier (laser mixture: 81% He, 12% $^{13}C^{18}O_2$, 8% N).

The 28 GeV/c AGS proton accelerator has been adapted to give to our area (D line) one of the 12 internal proton bursts [Single Burst Extraction (SBE) operation]; this isolated burst contained about 10^{12} protons and it was about 20 ns wide. These protons directed onto our pion-production target were used to generate the burst of low-energy negative muons (about 50 ns wide) to be sent into our helium gas box. Naturally the SBE operation had to be synchronized with our $^{13}C^{18}O_2$ laser firing so that the negative muons and the laser

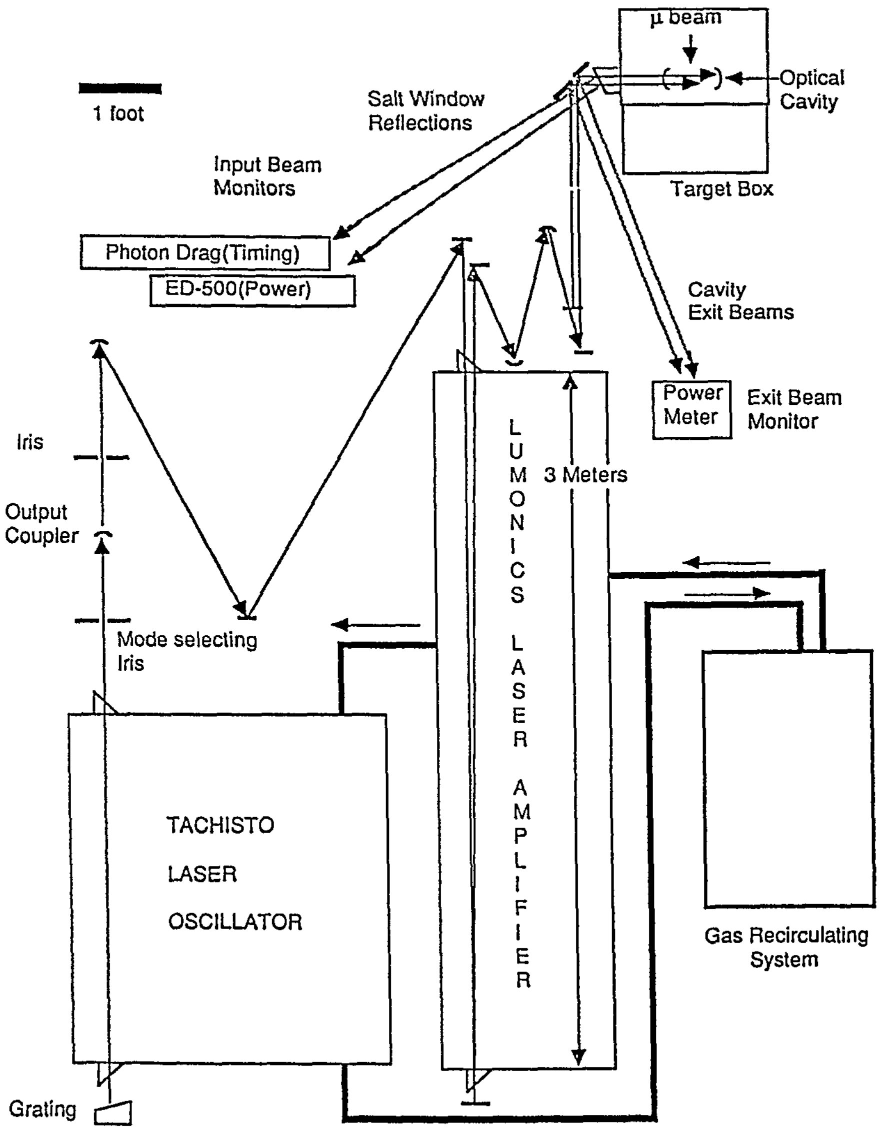

Fig. 3 : Schematic diagram of laser system

radiation, would be present together in the multipass cavity target; Fig. 5 shows the scheme of the different timings.

Table 3 gives the relevant figures for the muon beam (AGS operation: normally 1 burst each 1.4 seconds).

The number of μ^--stops in the table refers to the volume $\bar{V}$ 'seen' by the X-ray detectors: this volume is bigger than the volume

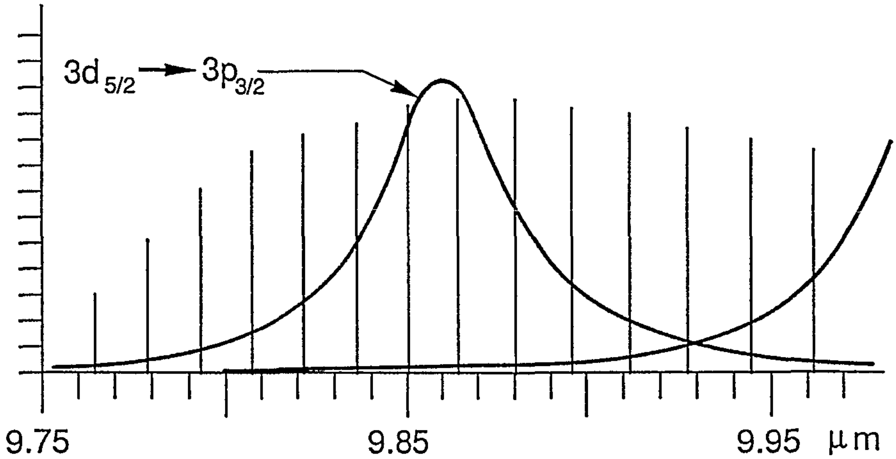

Fig. 4 : $^{13}C\,^{18}O_2$ laser transitions: 001-020 [II] P branch.

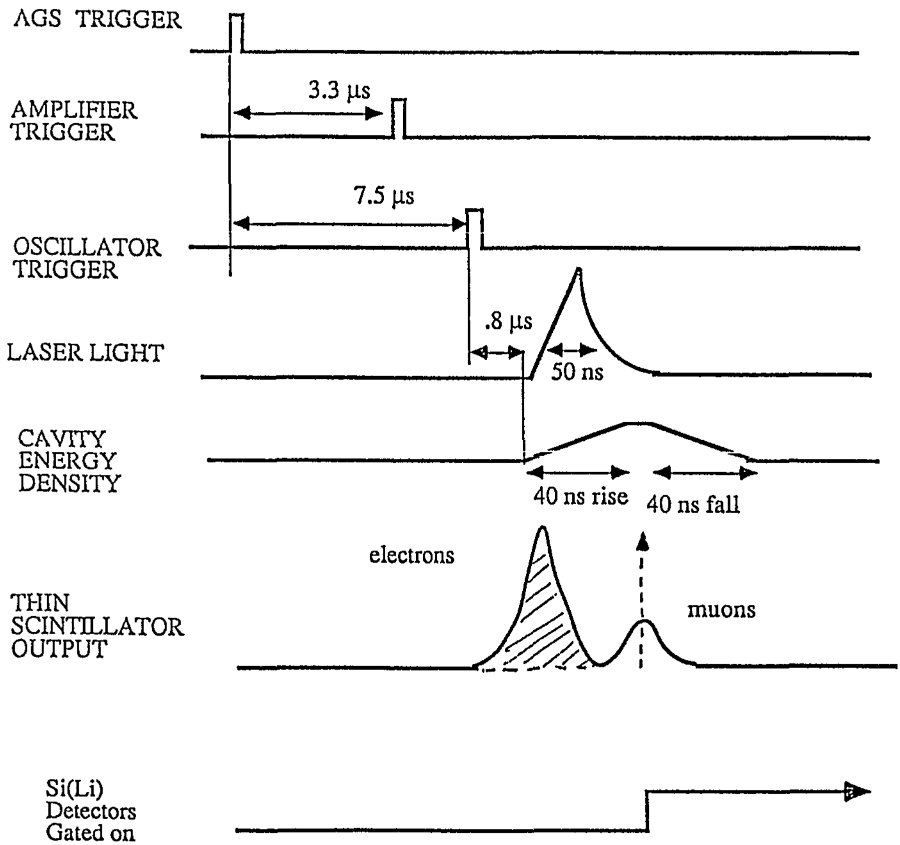

Fig. 5 : Timing of laser system.

Table 3
Muon beam parameters per burst (10^{12} protons on target)

Momentum (MeV/c)	μ^--stops in cavity	μ^--total over 5 cm x 15 cm	Electrons/muons	Si-Li counts
25	300	1000	8	0.65

V illuminated by the reflecting laser beam. Let us put $f = V/\bar{V}$ (f is between 0.7 and 0.5).

Since the pulsed muon beam is essentially instantaneous compared to the integration time of the X-ray detectors, only one count can be accepted by each detector during a single AGS burst. The selection of an optimum integration time is a compromise between the improved resolution of a long time and the possible reduction in background interference using a shorter integration time. The figure in the last column of Table 3 (which represents the sum of all pulses in one Si-Li detector) is the result of such a compromise: in that figure (obviously obtained without laser firing) there is the contribution of the accidental background (for example, neutrons from the pion-production target) as well as the contribution of the physical background (given, for example, by the muon's decay electrons or cascade X-rays from muons stopped in the helium within the cavity volume V and directly seen by the Si-Li detectors). Clearly, here we have the typical difficulty of working with a pulsed beam; to arrive at the given figure of 0.65 we had to spend a great deal of time in trying various shielding arrangements.

Many runs have been done without the firing of the laser, in order to establish the yield of K_β X-rays (our natural physical background) emitted in the prompt de-excitation processes of the helium muonic system; in this region of pressure (1-3 atm) no measurements exist. For us it is essential to know this rate in order to compute the number of events we have to take with the laser on, so as to resolve the peak of the stimulated K_β X-rays over the background.

In addition, this region of pressure seems to be rather important for an understanding of possible mechanisms [8, 9] through which the 2S muonic helium ion, at higher pressures, is so abundantly present after many hundreds of nanoseconds.

The results of the measurements [6] of the K_β yield when negative muons are stopped in a helium gas target at pressures of 1 and 3 atm are presented in Fig. 6 together with all measurements done by other groups on the K_β yield at different pressures. This figure shows that the K_β yield, after about 5 atm, becomes almost proportional to the gas density. This figure also shows our results

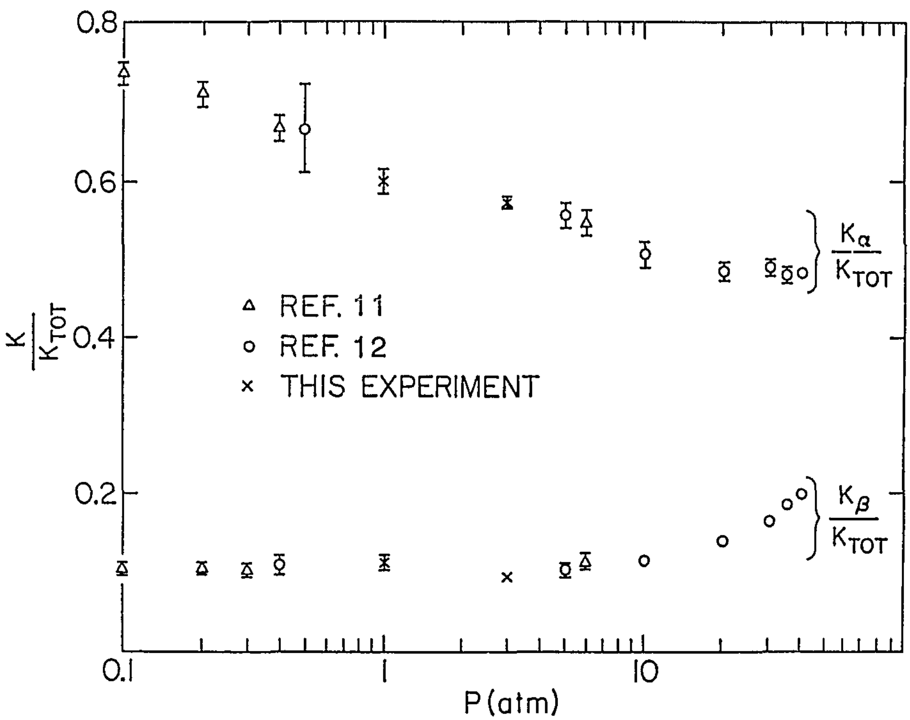

Fig. 6 : Experimental values for K_α/K_{tot} and K_β/K_{tot} as a function of target pressure.

concerning the K_α intensity together with the results of the other groups. At present, there are no theoretical calculations able to reproduce these results.

The practical conclusion we have drawn from Fig. 6 is that, since the K_β yield is a great nuisance, we have chosen to work at 3 atm.

The first runs were done with normal $^{13}C^{18}O_2$ gas in the laser; this was just to study the effect of the laser discharges on our electronics. Obviously it took some time, in these conditions, to learn to shield all the sensitive parts of the apparatus (data taking and monitoring electronics).

Our last runs were with the (expensive) isotopic gas $^{13}C^{18}O_2$ in our TEA laser system. We ran for some days with the diffracting grid set at λ = 9.8595 µm (presumed resonance value), firing the laser with every other beam burst. During this period, the repetition rate of the AGS was 1.4 s. It is easy to see that a 'good' quantity to look at to observe stimulated laser transitions is the ratio K_β/K_α. From the analysis of the spectra we obtained for the following quantity (o = laser on; f = laser off)

$$Y = \frac{(K_\beta/K_\alpha)_o - (K_\beta/K_\alpha)_f}{(K_\beta/K_\alpha)_f} ,$$

the experimental value

$$Y_{exp} = (0.012 \pm 0.014) .$$

The expected value for Y (assuming that we centred the wavelength) is

$$Y_{th} = f \times 0.034 = 0.017 ,$$

putting the f parameter earlier mentioned equal to 0.5.

From these results we concluded that in order to do a significant measurement, i.e. comparable or competitive with the 2S-2P difference measurements [1], it is necessary to collect a total of many thousands of K_β: this is possible, in principle, but with the X-ray detecting system at our disposal we need to do a run too long to be realistic.

A large array of X-ray detectors (total surface 60 cm^2 at least), is needed with high segmentation and prompt enough to reject events from the earlier electrons contained in the burst (see Fig. 5). At present we are investigating various options to solve this problem.

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