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(Laser, Atomic and Molecular Physics)

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ABSTRACT

The stimulated emission reduction and the electromagnetically induced transparency due to atomic coherent effects in a V–shaped configuration are observed by spectroscopy technique. The experimental results show that the absorption coefficient at maximum coherence is reduced to about 80% of the maximum absorption α_0, which is in the case without the coherence effect. Meanwhile we also observed the population trapping in the two excited states and there is no decay via spontaneous or stimulated emission to the lower state.

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Preface

The ICTP-LAMP reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

These reports aim at informing LAMP researchers on the activity carried out at ICTP in their field of interest, with the specific purpose of stimulating scientific contacts and collaboration of physicists from Third World Countries.

If you are interested in receiving additional information on the Laser and Optical Fibre activities at ICTP, kindly contact Professor Gallieno Denardo, ICTP.

Recently there has been considerable interest in the quantum interference effects[1-10], which play an important role in an atomic system affecting the emission and absorption spectra. Many interesting phenomena depend on these interference effects, for example, laser without inversion, electromagnetically induced transparency and refractive index enhancement[1,2,11]. To obtain these effects a coherence between the levels must be established, possibly by microwaves resonant with the level transition or via initial preparation or by Raman interaction[2,4]. It is well known that maximum two-photon coherence leads to population trapping in Λ-shaped three-level systems interacting with resonant laser fields[9,10]. The population is equally trapped in the two lower levels due to optical pumping of the ground-state sub levels into a coherent superposition state. Under this condition, the atom is decoupled from the laser fields. This effect was observed nearly twenty years ago in an optical pumping experiment by Alzetta et al.[10] and in an atomic beam experiment by Gary et al.[11]. For the V-shaped three-level system Cohen-Tannoudji, Reynaud[12] and Scully, Zhu[2] suggested that an effect similar to coherent population trapping should be expected. Bulbul et al. have theoretically studied that interaction of a closed V-shaped three-level system with two laser fields having arbitrary intensities[13]. They show that at sufficiently high intensity and exact resonance, half the population should be in the ground state and half in the coherent superposition of the two upper states. In this case, the strong coherence reduces the stimulated emission and almost cancels the one-photon absorption spectrum, and the absorption medium becomes transparent[2,13]. In one recent report, Bolero et al. have observed a transparency effect in a Λ-shaped level system by interference between two dressed states[14]. For the V-configuration a resonant saturation spectroscopy in fast accelerated atoms beam of Ne* and Ca* had been carried out, however, the transparency effect and the stimulated emission reduction effect due to coherence quantum interference were not reported[15].

In this paper we report an experimental observation of the stimulated emission reduction effects and the electromagnetically induced transparency of medium due to the atomic coherent interference in the V-shaped level system. In this experiment, sodium vapour is used as an absorptive medium. It is well known that sodium is not a good three-level atom, because of the ground state hyperfine splitting. This fact, may be, has important consequences in the experiment, because at high intensity levels of light field optical pumping in the ground state is significant. If this is the case, then the two-photon coherence has little to do with the experimental observation. However, if the two upper states are prepared in a coherent superposition, then the population of upper levels undergo no spontaneous or stimulated radiative decay, therefore, the optical pumping becomes not significant[2]. In this paper we report two experiments to demonstrate the transparency of the medium and the population trapping in the excited states due to atomic coherent effects.

As shown in Fig. 1, if the atoms are moving with velocity V in a standing wave field and the laser frequency ω_l is tuned to a frequency ω_0, that is exactly halfway between |2> and |3> states. Here $\omega_0 = (\omega_1 + \omega_2)/2$, and ω_1 and ω_2 are two atomic transitions. Since the standing wave consists of two counter propagating waves E^+ and E^-, and moving atoms have a velocity component V_z along the travelling waves, therefore the frequencies of the travelling waves E + and E- are Doppler shifted by a mount of $\pm KV_z$ to resonate with the two atomic transitions of |1> to |2> and |1> to |3> . In this case both the counter-propagating travelling waves interact with one of the two groups of atoms having $Vz = \pm c(\omega_1 - \omega_2)/2\omega_0$ via the two atomic transitions, as shown in Fig.1. Subsequently, the two travelling waves couple the two different upper states to a common lower state |1>, the coherence between |2> and |3> is established by the strong coherent travelling waves of frequencies ω_1 and ω_2. The external fields change the absorption profiles from those of bare atoms, leading to the possibility of reduction of absorption of the medium. According to theoretical calculations, the induced polarization at frequencies ω_1 and ω_2 is given by $P_1(\omega_1) = d_{31}\rho_{31}$ and $P_2(\omega_2) = d_{21}\rho_{21}$. Here, d_{31} and d_{21} are dipole moments, and ρ_{31} and ρ_{21} are off-diagonal density matrix elements respectively. Because, the one photon-absorption is proportional to $\mathrm{Im}\rho_{31}$ and $\mathrm{Im}\rho_{21}$, which are given as[13]

$$\rho_{21} = -\frac{\Omega_1(\rho_{22}-\rho_{11})}{2[\Delta_1 - i(1/T_2)_{21}]} - \frac{\Omega_2\rho_{23}}{2[\Delta_1 - i(1/T_2)_{21}]} , \quad (1)$$

$$\rho_{31} = -\frac{\Omega_2(\rho_{33}-\rho_{11})}{2[\Delta_2 - i(1/T_2)_{31}]} - \frac{\Omega_2\rho_{32}}{2[\Delta_2 - i(1/T_2)_{31}]} . \quad (2)$$

Here Ω_1 and Ω_2 are the one-photon Rabi frequencies, Δ_1 and Δ_2 are the one-photon detuning, (1/T)ij are the dephasing rates for the off-diagonal density matrix elements, ρ_{23} and ρ_{32} express the coherence between |2> and |3>. For exact resonance and large equal Rabi frequencies, there is almost complete cancellation between the two terms that contribution to ρ_{21} and ρ_{31}, so the medium becomes non absorptive[2,13].

We first describe the experiment to confirm the existence of transparency of the medium induced by the atomic coherence effects. We use a standard saturation spectroscopy techneque[16], as shown in Fig.2, to detect the transparency. A cell containing sodium vapour is placed in a laser standing wave, in which the sodium vapour pressure is kept low enough, by temperature controlled heater. The cell temperature is about 150^0C, and the mean free-path of the sodium atoms is considerably longer than the dimension of the cell, so that atoms do not suffer from collisions effects. The cell, a Pyrex cylinder 2.5cm in diameter and 25cm long is located at the centre of the three pairs of Helmholtz coils and a magnetic field of 1.7 G is perpendicular to the cylinder axis Z. The two counter propagating waves E^+ and E^- pass through the cell, one of which is used as a pumping beam and chopped by the chopper 1 (the chopper 2 is open,), the other one is used as a probe beam to monitor the variation of the laser transmission through the sodium vapour. A Coherent 699-21 frequency stabilised dye laser, is tuned to the sodium D_1 line resonance. The laser beam of TEM_{00} mode radiation of intensity $5mW/cm^2$ is directed along the Z axis and retro-reflected by a mirror Pr. The laser beam is 3mm in diameter and circular polarized. Two glass plates, P1 and P2, are inserted into the path of the standing wave, and partial of the travelling waves, about 3%, are reflected out from the glass plates, which are used for detection. A phase sensitive detection technique is used to measure the transparency of the sodium vapour.

The presence of the coherent interference effect is evident in the saturation spectrum of the D_1 hyperfine structure of the sodium atom, as shown in Fig. 3. The spectrum is recorded by the photo detector Pd1 to show the transparency effects of the medium. The left and right peaks (a, b) arise from the $3S_{1/2}, F=1$ to $3P_{1/2}, F=1$ and $3S_{1/2}, F=1$ to $3P_{1/2}, F=2$ transitions respectively. In thise case both travelling waves are resonant with one velocity group of atoms having a component $V_z=0$ in the direction of standing wave, it means that the atoms are moving perpendicular to both travelling waves. The central peak indicates the atomic coherent effects, which can be happen only, when the laser is tuned to the exactly halfway between $\omega_1$and ω_2, as indicated above. This clearly shows that the peak induced by the atomic coherence of the upper levels is much higher than the neighbouring peaks of the saturation spectrum. It is known that in the weak standing wave the coherent interference of the states in negligible, the amplitude of the peak a is proportional to $|d_{12}|^4$, the peak b is proportional to $|d_{13}|^4$, and the central peak is proportional to $|d_{12}|^2\ |d_{13}|^2$[17,18] For the transitions of $3S_{1/2}, F=1$ to $3P_{1/2}, F=1$ and $3S_{1/2}, F=1$ to $3P_{1/2}, F=2$, we have $|d_{12}| \approx |d_{13}|$. Therefore, the three peaks have the similar amplitudes[15]. However, in the strong standing wave field, the Rabi frequency $\Omega_1=\Omega_2=6.5MH_z$ the strong coherent effect leads to cancellation of the one-photon absorption. The central peak is 7 times higher than its neighbours, as shown in Fig.3. We have also measured the Doppler absorption profile of the sodium vapour from detector Pd2. The result shows that the absorption coefficient $\alpha_c$at maximum coherence is reduced to about 80% of the maximum absorption α_0 without atomic coherence effects. In this experiment we have found that the effect of atomic coherent interference is very sensitive to the direction and intensity of the magnetic field. The maximum transparency is observed when the direction of the magnetic field is perpendicular to the propagating direction of the laser beam, which is the axis of quantization. The magnetic field will cause a mixing of all Zeeman sub levels M_F of a particular hyperfine state F. As a result, all sub levels are involved in the coherent interaction with the light. The sodium atom is rather similar to the closed V-shaped three-level system, increase of the magnetic field does not destroy the atomic coherence of the upper states.

We now describe the experiment to observe the population trapping in the two excited states due to atomic coherence effects. According to the theoretical calculation, as the atoms are initially in the ground level |1>,

$$\rho_{11}^{0} = 1 , \rho_{22}^{0} = \rho_{33}^{0} = 0, \tag{3}$$

when the time is tends to infinity,we obtained that

$$\rho_{11}(t) = 1/2 , \rho_{22}(t) = \rho_{33}(t) = 1/4., \tag{4}$$

which is not a function of time. The population is therefore trapped in the upper levels and the atoms will not decay to the lower level via spontaneous or stimulated emission. To confirm this, we have measured the population distribution of atoms in the ground state . The experimental scheme is shown also in Fig.2., here we added a probe beam 3, which is propagating in the direction of the standing wave but separated from it by 6mm, to detect the changes of population distribution in the state $3S_{1/2}$, $F = 2$. The probe beam 3 is coming from the same Coherent Laser 699-21 and has the same frequency as beam 1 and beam 2. In the low pressure cell, if the laser beam 1 creates a hole in the velocity distribution of atoms, then according to the principle of saturation spectroscopy technique the hole can be detected by the probe beam 3[19]. In this experiment, first we take off the mirror Pr , then the beam 1 and beam 3 become two counter-propagating waves. When the laser frequency ω_l is tuned to exactly halfway between |2> and |3> states, then the beam 1 creates two holes on the population distribution of the ground state by optical pumping. If the beam 1 is modulated by the chopper 2 (chopper 1 is open), then the probe beam detect holes as an peak in spectrum and which is two times larger than the neighbouring peaks. The Fig.4 (a) shows the detected absorption spectrum from Pd3 by the probe beam 3, which indicate the burned holes by optical pumping effects[19]. Now we put the mirror Pr back into the beam 1,and which is retroreflected to form a standing wave as in our transparency experiment, but the probe beam is not changed. The detected spectrum by the probe beam 3 is shown in Fig.4(b). It shows that the centre peak in standing wave is smaller than that in the travelling wave at cross over resonance. If optical pumping effect is the dominant effect in the standing wave, then the centre peak should be larger than the peak in travelling wave, because the field intensity of the standing wave is twice as strong. However to compare the two centre peaks in Fig.4 (a) and (b), the hole burned in the standing wave is much smaller than the hole burned by optical pumping in travelling wave. The reduction of the centre peak in the standing wave is due to the atomic coherent effects. In this case the population in the upper levels is trapped and will not decay to the lower levels via spontaneous or stimulated emission, only when the atoms go out from the standing wave, where atomic coherence effects no longer exist, the spontaneous emission will take place and part of the atoms can be decay to $3S_{1/2}$ $F=1$ state. Therefore, the hole burned in the standing wave is smaller due to the population trapping effect. It should be noted that in the case of standing wave, the signal to noise ratio is not good, because the noise level is four times larger than that in the travelling wave.

In conclusion, we find that it is possible to establish atomic coherence between the upper levels of the V-shaped configuration by a coherent standing wave. Under this condition , the stimulated emission is reduced and population of atoms is trapped in the excited states, then the medium becomes transparenct. We also found that the atomic coherence effects is very sensitive to the external magnetic field, the maximum transparency is observed, when the direction of the magnetic field is perpendicular to the propagating direction of the laser beam. It is known that sodium is a natural candidate for experiments of laser without inversion, electromagnetically induced transparency and refractive index enhancement[1,2,11], therefore, it may be possible to observe some basic features of these effects by means of the principle demonstrated in our experiment.

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FIGURE CAPTIONS

Fig. 1. Partial energy-level diagram of sodium (not to scale) and atom moving in a standing wave.

Fig.2. Experimental scheme. Beam 1and 2 are used for transparency experiment, beam 3 is used for population trapping experiment.

Fig.3. Saturation spectrum of D_1 hyperfine structure of atomic sodium in a circular polarized laser standing wave field. The peaks labelled a and b correspond to the transitions in the inset. The peak c is due to atomic coherence effects.

Fig. 4. Absorption spectrum of D_1 hyperfine structure of atomic sodium detected out side the pumping beams.(see text)

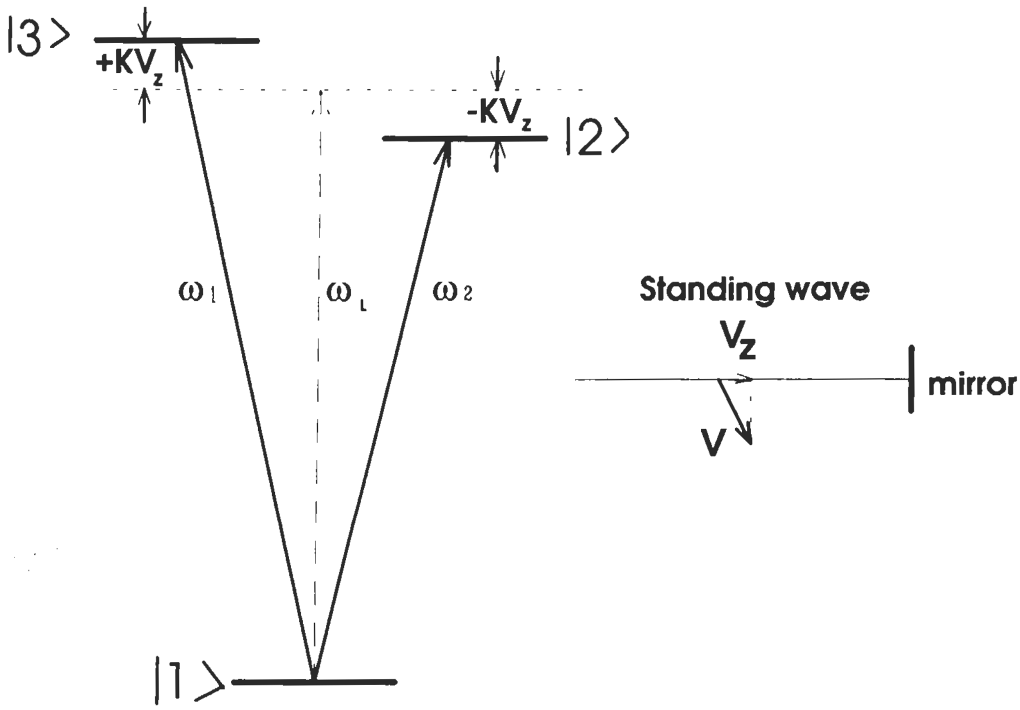

|3>
+KV_z
-KV_z
|2>
ω1
ωL
ω2
Standing wave
V_z
mirror
V
|1>

Fig.1

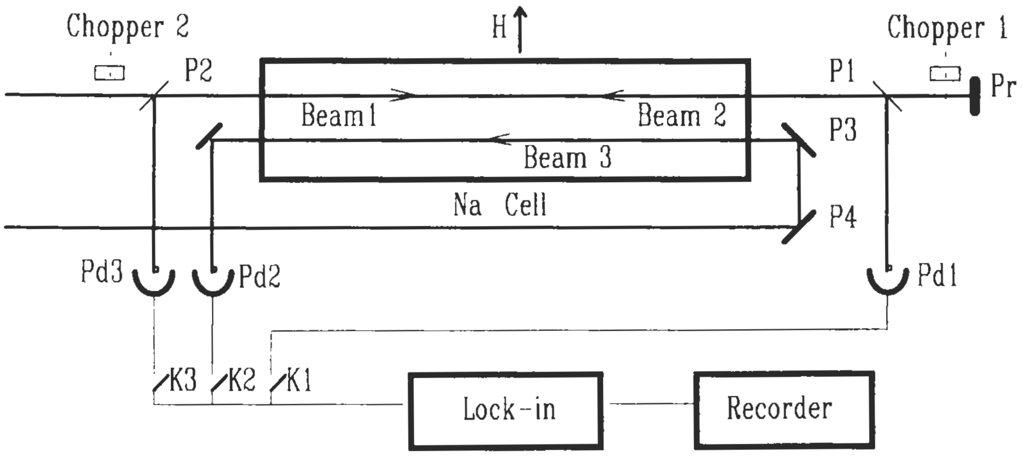
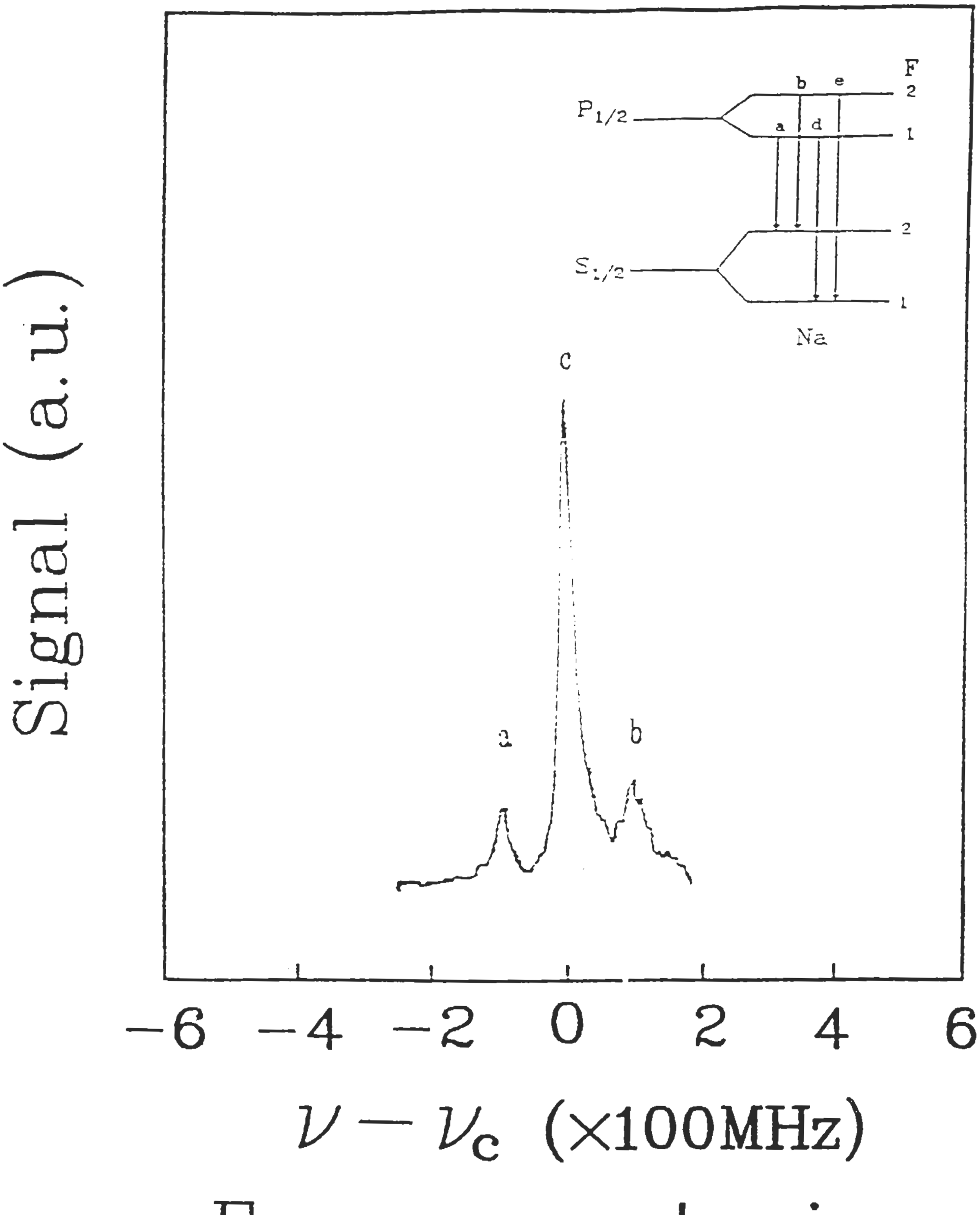

Chopper 2
H
Chopper 1
P2
P1
Pr
Beam1
Beam 2
P3
Beam 3
Na Cell
P4
Pd3
Pd2
Pd1
K3
K2
K1
Lock-in
Recorder

Fig.2



$P_{1/2}$
$S_{1/2}$
F
a
b
d
e
2
1
2
1
Na
c
a
b
Signal (a.u.)
−6 −4 −2 0 2 4 6
$\nu - \nu_c$ (×100MHz)
Frequency tuning

Fig.3

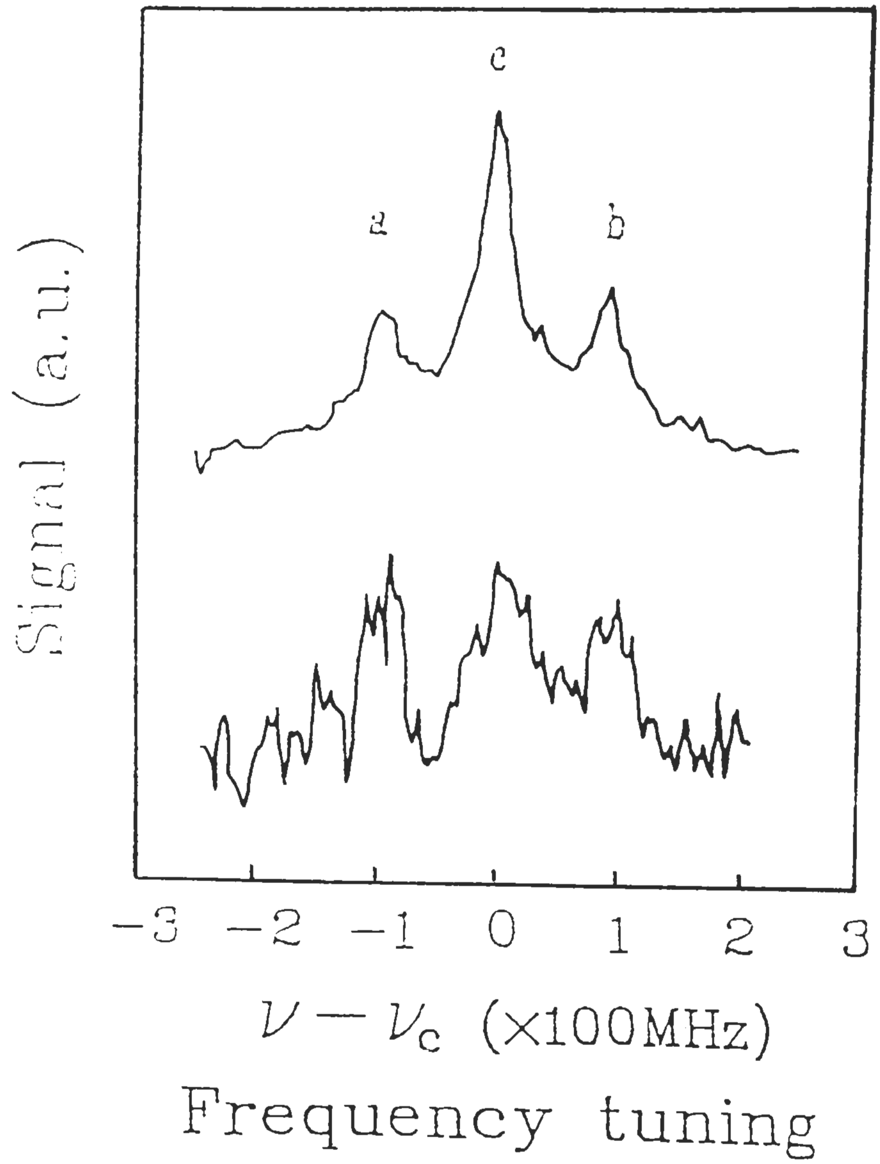


Fig.4