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LINE SHAPES OF DOPPLER-FREE RESONANCE IN SRFM: STRONG ATOM-WALL INTERACTION AND PRESSURE EFFECT ON THE FREQUENCY SHIFT OF AN ALKALI VAPOR

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Abstract

The attractive potential energy between the atoms of rubidium vapor and a dielectric wall has been investigated by monitoring the reflection light at the interface. The atom- wall interaction potential of the form $V(z) = - C /z^3$ (z: atom-wall) allows to predict experimental results only for weak regime, i.e., where $C << 0.2$ kHzμm^3. In the strong interaction case, the dispersive line shape is turned into an absorption-type line shape. The influence of atomic density on the shift of the selective reflection resonance relatively to the frequency of unperturbed atomic transition is found to be red with a negative slope. This technique opens the way to characterize the windows made of different materials thin films.

Keywords: *Atomic Transition, Selective Reflection Spectroscopy, London Van der Waals Interaction, Attractive potential, Spectral Line width and Shift, Collisional effects.*

Résumé

La mesure de l'énergie potentielle attractive des atomes du rubidium vapeur par une paroi diélectrique s'effectue par l'enregistrement de la lumière réfléchie à l'interface. Le potentiel d'interaction de la forme $V(z) = - C /z^3$ (z: distance atome-paroi) prédit les résultats expérimentaux seulement pour le régime faible, c'est-à-dire lorsque $C << 0.2$ KHzμm^3. Dans le cas de régime fort d'interaction, la forme dispersive de raie perd son allure pour devenir typiquement absorpative. Les résultats obtenus montrent que la densité atomique induit un déplacement spectral vers le rouge, de pente négative, du centre de résonance de la réflexion sélective relativement repéré à une fréquence invariable de la transition atomique. Cette technique donne lieu à des applications en vue de la caractérisation de parois de différents matériaux en couche mince.

Mots clés: *Transition atomique, Spectroscopie de réflexion sélective, Interaction de London van der Waals, Potentiel attractif, Déformation spectrale de raie et déplacement, effets collisionnels.*

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ملخص

إن قياس الطاقة الكامنة الجاذبة بين ذرات بخار "الروبديوم" Rb والطبقة العازلة يتم عن طريقة تسجيل شدة المنعكس عند الحد. فكمون تأثير الذرة والسطح المتغير حسب العبارة $V(z)=C/z^3$ [z: وضعية الذرة عن السطح] يمكن تنبؤ النتائج التجريبية فقط في حالة النظام الضعيف: أي من اجل $C<<$. 0.2KHzμm^3 أما في حالة التأثير الشديد أن تشتت الطيف ينقلب إلى شكل الامتصاص النمطي.

إن الكثافة الذرية تسبب انزياحا ذو ميل سالب: نحو الاحمر لوضعية مركز التجاوب لإشارة الانعكاس الانتقائي بالنسبة لوتر طيف تابت الشروط. هذه التقنية تفتح مجالات تطبيقية لتخصيص الطبقات الرقيقة من مختلف المعادن.

الكلمات المفتاحية: *الانتقال الذري، الكمون الجاذب، التأثيرات التصادمية، تفاعل لندن-فان در فالس,*

In order to probe specifically a neutral atom interacting to the neighborhood wall, one interests to the reflected light by the wall, supposed transparent, in contact with the resonant vapor. It may be viewed as an interaction process between the atomic dipole and its electric image induced in the partially reflecting surface. The reflectivity from the boundary of the atomic gas is essentially associated to the atoms response confined in a layer with a thickness of $z < \lambda/2\pi$ (z: atom-wall distance). The technique being called a selective reflection (SR) when combined with a frequency modulation (FM) to the incident beam proved to be efficient for evaluating concentration broadening [1-3]. Its spectral dependence reveals Doppler-free resonance at small atomic concentrations (where collisional broadening is smaller than the Doppler line width). In all experiments of selective reflection recently intensified, the surface-interaction observed alone seem to be the Van der Waals attraction. In the present work we demonstrate that the attractive strength for interaction strong regime is responsible for a previous absorption-line shape (with an inversion phase), on the theoretical selective reflection resonance (Fig.1). As previously predicted [4], the observed line shape has been interpreted by a theoretical analysis taking into account a z dependence for the resonance frequency,

$$\omega_0(z) = \omega_0 - A\gamma / (2k^3) \qquad (1)$$

where A is the strength of the Van der Waals interaction at a distance $z_0 = k^{-1} = \lambda/2\pi$. This model gives access to the long range interaction potential [3], which cannot be analyzed by mechanical techniques.

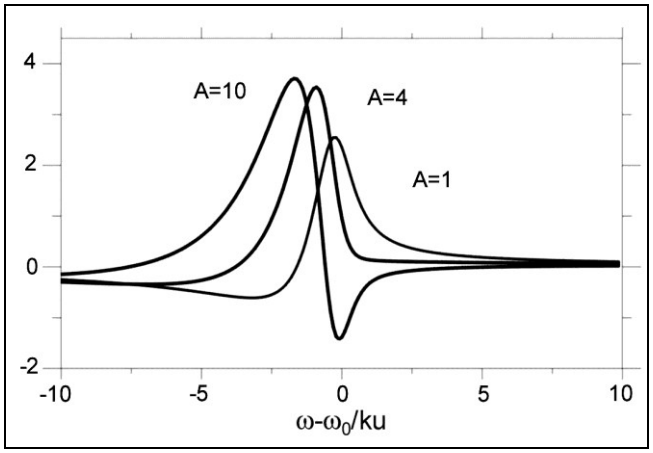

Figure 1: Theoretical (FM) SR line shapes for a strong interaction regime at different attractive potentials : A = 1, 4, 10.

Under the above assumptions, one gets the general model described elsewhere [3], the influence of the parameter A on the FMSR, is illustrated in figure 2, where a typical prediction of a red-shift and asymmetries are more apparent. In the strong regime interaction, the red wing amplitude becomes more important and larger than the blue wing. For the 780.1nm line, it can be experimentally checked [3], that the collision effect has similar behavior, while the Van der Waals strength A does not exceed 0.2. The line shapes are moreover strongly depended on Rb atomic concentration.

Since the volume probed in SR spectroscopy is in the order of λ [5], a systematic comparison between (FM) SR and AMSA spectra allows to provide a sensitive method of observing wall-induced resonance shift (Fig. 2). A careful analysis with an excellent resolution in frequency of laser diode allows to reach the natural resonance width of the atomic transitions. As a result of the fitting at different Rb densities (or pressures) measured near the coldest part of the cell, illustrates in Figure 2c, we give the width γ_0 extrapolated at vanishing Rb pressure, and the self-broadening, and frequency shift for all hyperfine components (Table 1). Typical Rb pressure dependence of the shift is shown in figure 3, for the components $5S_{1/2}(F=1,2) \rightarrow 5P_{3/2}(F'=1,2,3)$. For these components, the characteristic slope for the shift versus Rb pressure is negative. Such a behavior means that the energy levels are shifted by pressure effect. Note also that, the single number C or A (cf. relation (1)) governs the predicted line shapes, and its value necessities the determination of the frequency scale of the experimental curves. These last, provides the transition line width. Our measurements for the self broadening (Table. 2) of all the hyperfine components on the transition ^{7}Rb ($\{5S_{1/2} \rightarrow 5P_{3/2}\}$, λ = 780.1nm) have to be compared with those of references [6-9], where the authors give the lifetime τ. We note that, the lifetime of an alkali metal between its two states may be depended on the natural width γ of the transition frequency as:

$$\gamma = 1 / (2\pi\tau) \qquad (2)$$

We obtain for the hyperfine components, $F \rightarrow F'$, (Tab. 1) the same width γ_0

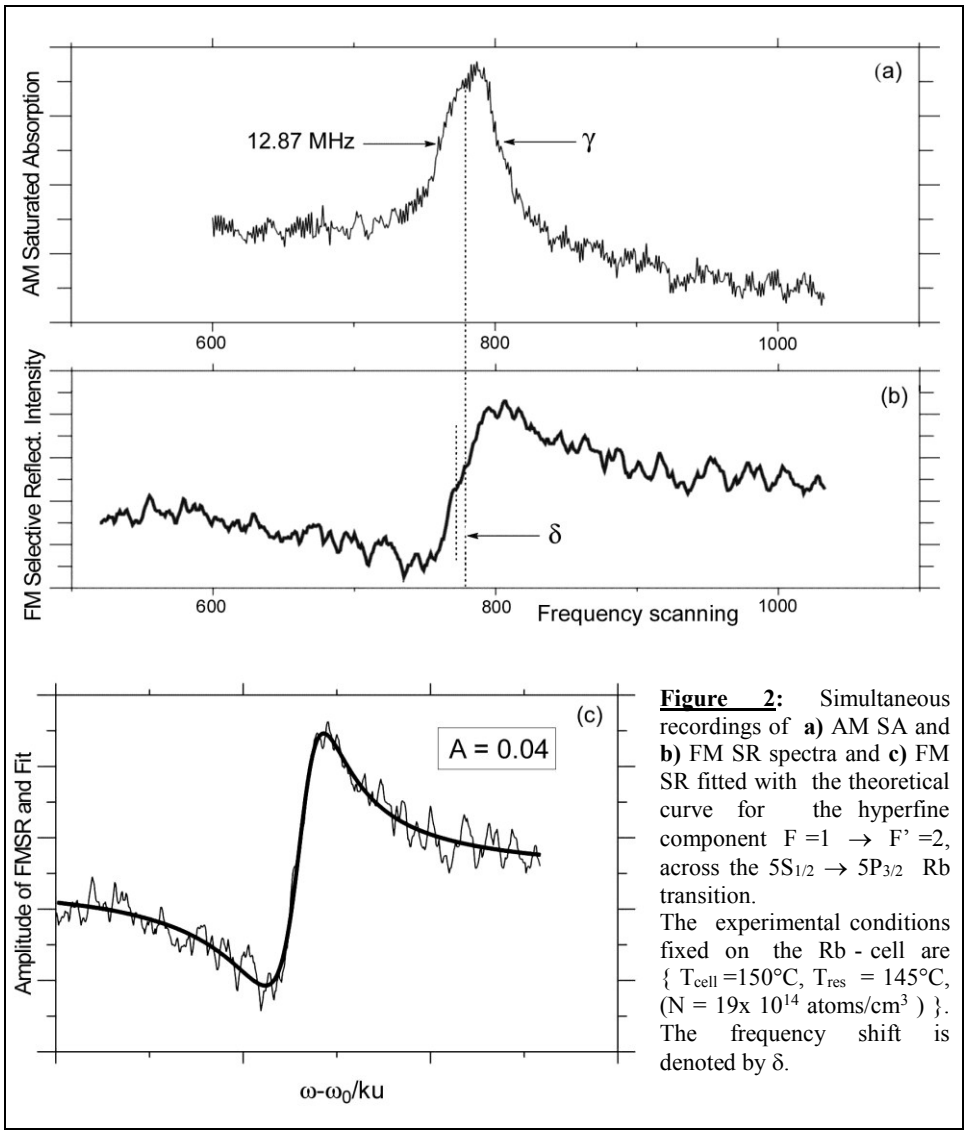

Figure 2: Simultaneous recordings of **a)** AM SA and **b)** FM SR spectra and **c)** FM SR fitted with the theoretical curve for the hyperfine component F =1 → F' =2, across the $5S_{1/2} \rightarrow 5P_{3/2}$ Rb transition.
The experimental conditions fixed on the Rb - cell are { T_{cell} =150°C, T_{res} = 145°C, (N = 19x 10^{14} atoms/cm^3) }. The frequency shift is denoted by δ.

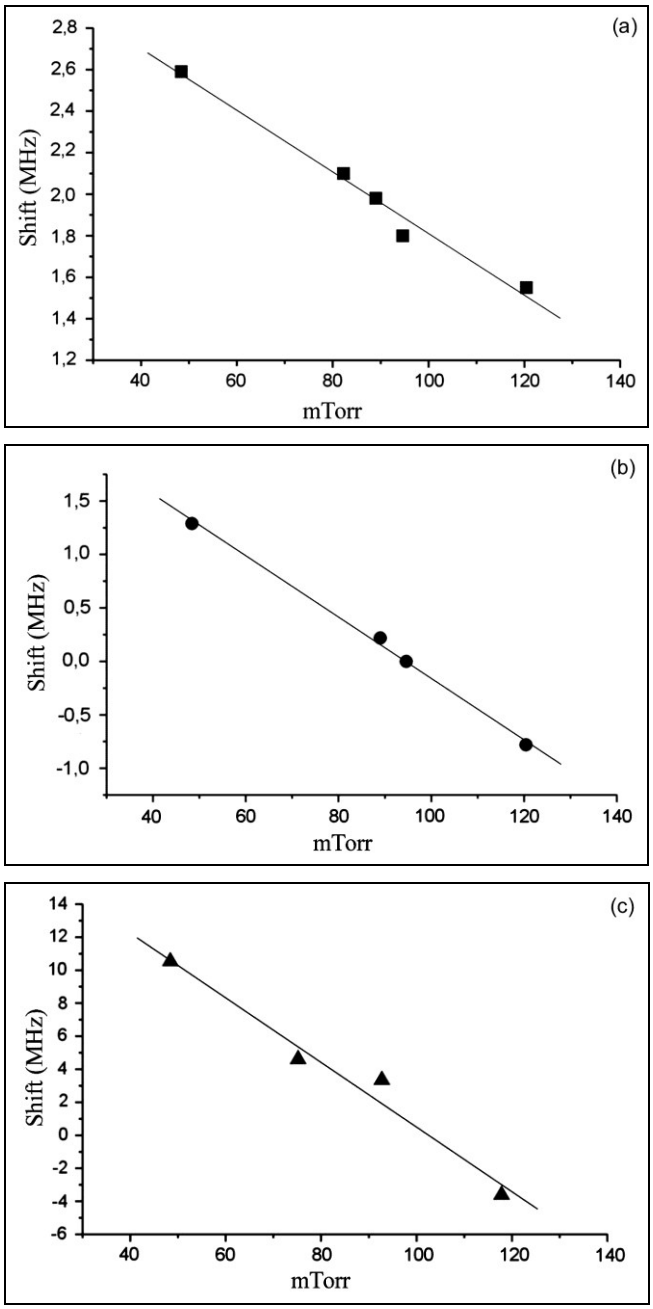

Figure 3: Experimental atomic pressure shifts δ (p) for the hyperfine components measured by comparison between AM SA and FM SR technique.

- **(a)** for the hfs $1 \rightarrow 2$,
- **(b)** for the hfs $1 \rightarrow 1$,
- **(c)** for the hfs $2 \rightarrow 2$.

at zero Rb pressure with an uncertainty of 10% (introduced by the Rb temperature measurement). In fact, there is only one exception which concerns the component $F = 1 \rightarrow F' = 2$, whose width, $\gamma = 6.12 \pm 1$MHz, is comparable to the one computed from the lifetime (relation (3)) of the $^2P_{3/2}$ state. Let us recall that, the power laser fixed to $\approx 0.45\mu$W of the incident beam under normal incidence on the vapor-glass window interface, has been optimized to suppress power broadening [10]. The optical pumping process induced by light intensity, $E_e - E_g = h\nu_{eg}$, gives rise to resonant peaks on the FMSR spectrum where each peak is associated with its proper saturation condition. The shift for $F = 2 \rightarrow F' = 3$ component has not been estimated because its reference is not observed in AM AS spectrum. As experimentally checked [10], the line width of the selective reflection resonance increases monotonously with the intensity of incident beam.

Transitions ^{87}Rb ($F \rightarrow F'$)	$1 \rightarrow 1$	$1 \rightarrow 2$	$2 \rightarrow 2$	$2 \rightarrow 3$
Shift/Rb pressure MHz/mTorr	- 0.028	- 0.014	- 0.19	------
γ_0 , MHz	11.05 ± 1	6.12 ± 1	11.18 ± 1	10.93 ± 1

Table 1: Self broadening and shift of Rb D_2 line components.

Lifetime ι x 10^9 (s) from refs	22.7 ± 0.3 [6]	26.7 [7]	27.0 ± 0.5 [8]	27.8 ± 0.9 [9]
Line width γ, MHz	7.01 ± 0.09	5.96	5.89 ± 0.10	5.72 ± 0.18

Table 2: Line width γ for D_2 line Rb transition calculated from the lifetime obtained by other investigators.

CONCLUSION

The results reported in this paper demonstrate that the reflected light beam from a gas interface allows to investigate atomic properties. High sensitivity of selective reflection spectroscopy performed in the vicinity of an atomic transition, under normal incidence, is an adequate tool for exploring the signature of long-range effects exerted by a dielectric wall on an optical dense vapor. The shift for the resonance frequency and line asymmetry observed in selective reflection spectrum are the contribution of the Van der Waals surface attraction. As expected from the attractive potential, the parameter A included in the theoretical model, changes with the atomic pressure, the FMSR line shape is red-shifted. For a concentration of atoms of N=19x10^{14} cm^{-3} in Rb-cell, the width of the RS resonance was 18.85MHz. Simultaneously to the SR signal demodulated by a lock-in amplifier and displayed by a recorder, a reference signal was plotted in an invariant conditions to provide a frequency scale. For a Rb-glass window interface, the best fit of a SR resonance with theory is obtained for A = 0.04 (i.e. $A\gamma/2$ = 0.37 MHz). Hence, the FMSR experiment performed on the $5S_{1/2} \rightarrow 5P_{3/2}$ [11] D_2 resonance line (λ = 780.1 nm) of Rb vapor at the interface with a polished glass window allows to assess an energy shift of the excited state to 0.7KHz μm^3, which is a red-shift.

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