the exact asymptotic freedom result.[11] In fact, the bound (25) may be verified "experimentally" for all β by numerical comparison of the MK string tension for $\lambda \geq 2$ with the corresponding Monte Carlo data.[12] At $d=5$, the argument fails to produce (25), since successive MK transformations hit a fixed point, and the exponential falloff of the strong-coupling regime is never reached, no matter how large we take $n(A)$.

The upper bound (25), though sufficient for establishing permanent confinement in the lattice theory, does not allow direct passage to the continuum limit. To demonstrate nonvanishing string tension in the continuum, a sharper estimate, one which converges to the exact value of the b_0 coefficient of the weak-coupling β function, is presumably needed.

The same development could be applied to the two-dimensional chiral $SU(2) \otimes SU(2)$ spin models. Analogous considerations, although with attending technical complications, should extend to general $SU(N)$.

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Experimental Study of Stimulated Radiative Corrections on an Atomic Rydberg State

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Light shifts of a Rb Rydberg level, induced by an intense nonresonant electromagnetic field, have been measured for the first time. Agreement between experimental results and theory is satisfactory.

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Light shifts in atomic spectra have been extensively studied. Many experiments have been performed for the case in which the frequency of the light is close to the frequency of an atomic resonance. A few calculations have been made to evaluate the influence of the blackbody radiation on the position of Rydberg energy levels.[1,2] This type of calculation generally takes into account the influence of all atomic energy levels including the continuum. Consequently, it requires knowledge of all of the oscillator strengths involved, which can be a serious difficulty. Similar difficulties appear in calculating the effect of an intense resonant electromagnetic (em) field, of strength F and frequency $\omega/2\pi$, on the position of a well-defined atomic energy level E_e. The corresponding shift ΔE_e is given by the general formula

$$\Delta E_e = \tfrac{1}{2}F^2 \sum_f \mu_{ef}{}^2 \left[\frac{1}{E_e - E_f - \hbar\omega} + \frac{1}{E_e - E_f + \hbar\omega}\right]. \tag{1}$$

However, for the case where the frequency satisfies

$$E_e - E_f \ll \hbar\omega, \tag{2}$$

a simpler calculation can be performed, as has been done in the framework of effective operators by Avan *et al.*[3] They actually treated the more general problem of the interaction of radiation with free or weakly bound electrons. Motivated by their theoretical results we have undertaken to study experimentally the shift of a Rydberg level due to its interaction with an intense and strongly nonresonant em field.

One of the most interesting features of the treatment by Avan *et al.* is that it has a simple physical interpretation: The most important part of the shift can be calculated by classical mechanics; it appears as an increase of the mean kinetic energy of the electron due to its rapid forced oscillation in the em field. A straightforward calculation gives

$$\Delta E_e' = e^2F^2/4m\omega^2, \qquad (3)$$

which depends on the electron charge and mass, and on the amplitude F of the radiation electric field of frequency $\omega/2\pi$.

Rydberg levels of atoms are convenient because they satisfy the "high-frequency condition" [Eq. (2)]. However, the atomic system posesses other levels which do not satisfy this condition, and these levels can have a dramatic effect if they are close to resonance ($E_e - E_f \approx \hbar\omega$). Fortunately, they give rise only to a limited number of terms in Eq. (1), and they can be evaluated separately. It will be shown below that for our experiment the contribution of such terms to the shift of the Rydberg level is several orders of magnitude smaller than the shift we observe.

Because measuring a level shift requires observing an atomic transition between two levels e and g, it is essential to examine the effect of the em field on both levels. The measured shift is the sum of the shifts ΔE_e and ΔE_g for the two levels. If g is the ground level of the atom, ΔE_g has a simple different physical interpretation: It is a light shift which is mainly due to the coupling with the resonance level. An evaluation of this shift is given below.

The experiment was performed on an atomic beam of rubidium atoms in a setup similar to the one described previously.[4] As shown in Fig. 1, Rb atoms cross an interaction region in which they experience two laser fields: A resonant uv field, tuned to the frequency of the transition between the ground state 5s and the Rydberg state 22p, and an intense nonresonant perturbing laser field provided by the 1.06-μm line of a neodymium-doped YAlG laser. As usual, the highly excited atoms are detected by electric-field ionization. In order to overcome synchronization difficulties, the two laser fields are generated by the same pump. The uv tunable-laser source has been described previously.[5] Its important characteristics are that it delivers single-mode light pulses of 20 ns duration with a repetition rate of 10 Hz and a spectral linewidth of about 50 MHz in the wavelength range around 295 nm. The residual infrared output energy at 1.06 μm of the frequency-doubled Nd-YAlG laser is sent through a Glan prism into a Nd-YAlG amplifier which is crossed twice. Because of a quarter-wave plate the linear polarization of the light is rotated 90°,

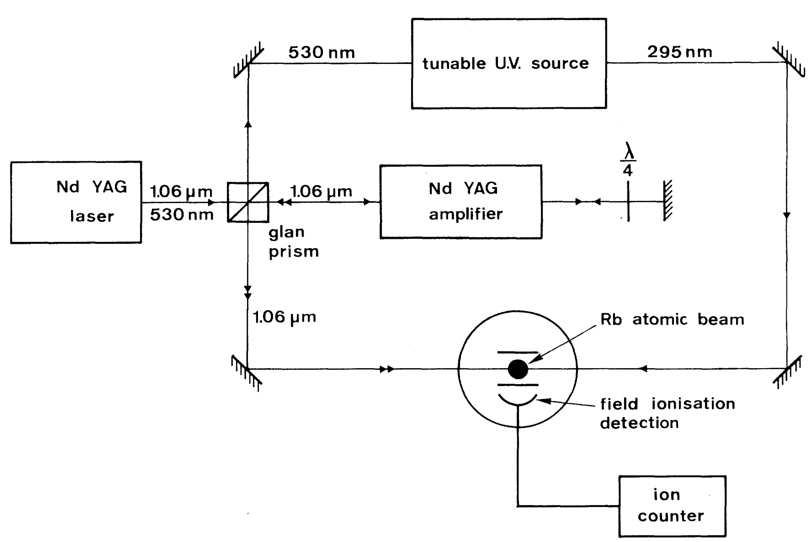

FIG. 1. Scheme of the experimental arrangement.

so that the amplified infrared (IR) beam is reflected by the Glan prism toward the atomic-beam apparatus. Such an arrangement makes it possible to generate IR light pulses with power ranging between 0 and 12 MW/cm^2. The two light beams propagate collinearly but in opposite directions. Special care has been taken to make sure that the uv beam actually probed the center of the infrared beam in the latter's TEM_{00} mode. A synchronous photograph of the two pulses displayed on a scope screen assured us that the uv pulse (20 ns time duration) probed the highest-energy part of the IR pulse (140 ns time duration).

The experiment employed the transition $5s\ ^2S_{1/2} - 22p\ ^2P_{3/2}$ of the most abundant isotope of Rb (the ^{85}Rb in the natural mixture). Each recorded spectrum shows a doublet structure which corresponds to the hyperfine splitting of the 5s ground state, the value of which is well known. The splitting, 3035 MHz, allows us to calibrate the frequency scale. Figure 2 shows a typical recording. The hyperfine doublet corresponds to the resonances recorded without the infrared power, marked $P_{IR}=0$. The two other resonances correspond to the same transitions but they are frequency shifted by the powerful infrared field. All these resonances were recorded during the same frequency scan, providing a reliable absolute measurement of the frequency shift. The recording also demonstrates that the spectral resolution is less than 60 MHz (in the uv range) in the absence of infrared power. In the presence of infrared power the resonances are broadened up to 120 MHz, which we believe is due to the effects of the slight inhomogeneity of the probed part of the infrared beam, and the fluctuations of the infrared peak power. All these effects produce a relative broadening with respect to the frequency shift of approximately 10%.

The power density of the strong IR field in the interaction region is a difficult quantity to measure. The power was measured by a power meter (Scientech) located outside the atomic-beam apparatus, and corrections were made to account for absorption by the windows. The peak power was deduced by monitoring pulse duration. (The pulse was displayed on a scope screen.) Finally, the diameter of the laser spot was determined with use of a detector mounted on a precision translator; it was found to be 0.8 mm at half-energy point.

In Fig. 3 we have plotted results of measurements of the frequency shift for various infrared peak power densities. It can be seen that all the experimental points lie on a straight line, as expected. To compare these experimental results to theory, notice that each measured value of the shift is the sum of two shifts: $\Delta\nu_e$ corresponding to the shift of the excited Rydberg state and $\Delta\nu_g$ corresponding to the shift of the ground state. For the Rydberg level, as mentioned previously, $\Delta\nu_e$ includes the shift we are searching for [Eq. (3)], and other parasitic shifts coming from nearly resonant coupling. Valence

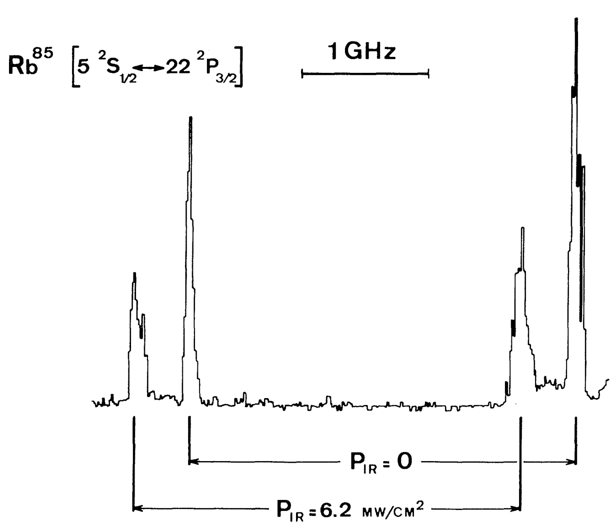

FIG. 2. Typical recording showing simultaneously the unperturbed ($P_{IR}=0$) and the perturbed structure ($P_{IR}=6.2$ MW/cm^2) of the $5\ ^2S_{1/2}$-$22\ ^2P_{3/2}$ transition of the ^{85}Rb.

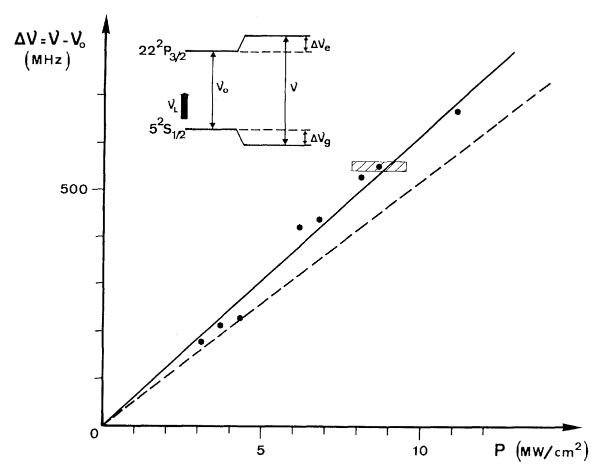

FIG. 3. Measured frequency shift of the transition vs the IR power density. The dashed line corresponds to the calculated curve. The experimental uncertainty corresponding to frequency measurements is ± 10 MHz, and the relative uncertainty due to the light power measurements is approximately 10%. These are displayed by the small rectangle around one experimental point.

levels which might have a significant role in the light shift of the $22p$ level due to the 1.06-μm laser field are $6s$, $7s$, $4d$, and $5d$. These are far from being resonantly coupled to the $22p$ level, at least 1700 cm^{-1} away. Their relative positions are such that their combined effects are partially cancelled. A rough evaluation showed that under these conditions the $5d$ level, which is expected to be responsible for the largest effect, contributes to the shift of the $22p$ level an amount of approximately 3×10^{-3} MHz/MW$\cdot$cm^{-2}. This is at least 4 orders of magnitude less than the measured shift, and is thus completely negligible.

With respect to the shift $\Delta\nu_g$ of the ground state, since it cannot be measured alone the best procedure is to calculate it as carefully and precisely possible. A calculation based on Fig. 1 has been carried out.[6] The result is $\Delta\nu_g = -26.3$ MHz/MW$\cdot$cm^{-2}. The dashed line in Fig. 3 corresponds to the sum of the two calculated shifts $\Delta\nu_e + \Delta\nu_g$, whereas the straight line corresponds to a least-squares fit on the measured shifts. Agreement between experimental and theoretical results is satisfactory.

To conclude, this experiment provides clear evidence for the shift of a Rydberg level, due to an intense and strongly nonresonant em field. It is of interest to note that in a pure quantum treatment, radiative corrections can be interpreted as the sum of spontaneous and stimulated radiative corrections. The net effect of spontaneous radiative corrections due to vacuum fluctuations is well known to be responsible for the Lamb shift. In the same spirit, the light shifts which have been studied in our experiment can perhaps be viewed as resulting from the stimulated radiative corrections induced by an intense and nonresonant em field.

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Study of High-Beta Magnetohydrodynamic Modes and Fast-Ion Losses in PDX

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Strong magnetohydrodynamic activity has been observed in PDX neutral-beam–heated discharges. It occurs for $\beta_T q \geq 0.045$ and is associated with a significant loss of fast ions and a drop in neutron emission. As much as 20%–40% of the beam heating power may be lost. The instability occurs in repetitive bursts of oscillations of ≤ 1 msec duration at 1–6-msec intervals. The magnetohydrodynamic activity has been dubbed the "fishbone instability" from its characteristic signature on the Mirnov coils.

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On the PDX tokamak, large-amplitude magnetohydrodynamic (MHD) fluctuations have been observed during plasma heating by injection of high-power neutral beams. The bursts of MHD activity are associated with losses of the energetic beam ions, which are injected nearly perpendicularly